The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016

Rev. 1, 4 May 2016: technical assumptions included explicitly on p.30

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Executive summary

In November 2013, ESA's Science Programme Committee decided that the L3 mission will address the theme 'The Gravitational Universe', responding to the science goals set out in the 2013 report of the Senior Science Committee. Accordingly, a Gravitational Wave Observatory is definitively in ESA's long-term planning, with a (programmatic) launch date of 2034.

A space mission exploiting laser interferometry has been under consideration, and studied in considerable depth, and in various forms, for 30 years. While promising to open and exploit a completely new window on the Universe, such a mission presents a set of demanding challenges for the measurement accuracies and associated technologies.

Accordingly, in late 2014, ESA's Director of Science and Robotic Exploration appointed an external committee, the Gravitational Observatory Advisory Team, to advise on the scientific and technical implementation of L3.

The Terms of Reference of the committee (given in Chapter 1) can be paraphrased as follows: (a) is the mission technically feasible? (b) is laser interferometry still the best approach to the measurement of gravitational waves from space? (c) how can the technical development of L3 be organised to minimize cost and schedule overruns?

The Committee was asked to report in mid-2016, and this document is the outcome of its work. Late in its tenure, two important events took place, which greatly consolidate the scientific and technical case for L3, and its timely implementation (see page 4 for a contextual overview): the launch and successful commissioning of LISA Pathfinder, and the first detection of gravitational waves. Specifically:

- launch of the technology demonstrator, LISA Pathfinder, took place on 2015 December 3. Although this report summarises how it impacts and enables the development of L3, ESA D/SRE has requested a decoupling of its detailed assessment; mainly because its detailed results are not yet available, but in part because the present Committee is not optimised for an in-depth evaluation. Nevertheless, at the time of submission, the test masses have been released, commissioning has been completed, science operations started on 2016 February 29, and the entire system appears to be functioning within specification;

- the most compelling and transformative scientific and technical result achieved in gravitational wave science to date was marked by the announcement of the first detection of gravitational waves by Advanced LIGO on 2016 February 11. In a single step, gravitational wave astronomy has been placed on a secure observational footing, opening the panorama to the next robust steps in a space-based gravitational wave observatory. And it is appropriate to emphasise that this result was obtained using laser interferometry, the same technique that this report recommends for L3.

An intermediate report was issued on 2015 June 15. The intermediate report already recommended that *laser interferometry* be kept as the baseline measurement strategy. It further identified a set of associated high-priority technology development requirements, which are largely independent of the precise satellite/payload configuration likely to be adopted, and therefore candidates for an early start in technology development. Following the report's presentation to the SPC, the highest priority technology development activities were subsequently initiated by ESA, with the dual goals of reducing risk, and securing a timely development schedule. The report also allowed ESA to initiate a consultation with potential collaborators about possible, nationally-funded, payload contributions.

In response to its terms of reference, the Committee's findings are as follows:

1. the Committee has undertaken a review of all known approaches to the measurement of gravitational waves. It has concluded that *laser interferometry* both fully responds to the science goals set out in the 2013 Senior Science Committee report, and is also sufficiently well advanced to offer a highly realistic prospect of implementation according to the L3 schedule. In terms of technology readiness and risk, it is preferred over any alternative;

2. the Committee appreciates that a second approach, based on *atom interferometry*, shows interesting potential. The Committee has encouraged the development of a full mission proposal to assess better its challenges, and its prospects for either a more secure, or a less costly, alternative. With ESA proceeding with plans for small innovative missions, a proof-of-concept atom interferometry experiment could be timely;

3. the Committee has re-evaluated the scientific capabilities of a gravitational wave observatory, quantifying and presenting the expected performance as a function of:
   - the number of interferometric baselines (2 or 3 arms, i.e. with 4 or 6 links);
   - the interferometric arm-length (between 1×10^6 km and 5×10^6 km);
   - the mission duration (2 years or 5 years);
   - test mass 'acceleration noise'.

   This is intended to provide ESA with a menu of scientific performance versus architecture (and, implicitly, cost) at whatever point in time that financial constraints, national contributions, international partners, and other boundary conditions are known more securely;

4. the Committee finds that the minimum architectural configurations studied may be considered as scientifically viable. However, the improved reliability and science performance offered by three *identical* spacecraft, and the enhanced scientific return of a longer-duration mission, with at least intermediate arm length, provides much greater impact;

5. the Committee has undertaken a detailed compilation of all technology developments (and major system trades) required for the laser interferometric approach, including the details of ongoing technology studies. To a first approximation, the technology development required is *independent* of the mission configuration;

6. the technology challenges of L3 are significant, but should not be overstated: a gravitational wave mission based on laser interferometry has had a very long development and study phase, and the techniques are well mastered on ground. LISA Pathfinder is now expected to retire many of the remaining risks of drag-free technologies;

7. the Committee has identified four high-priority, high mission impact, technology activities, not covered by LISA Pathfinder, which are recommended for immediate start: related to the optical architecture, the telescope, the laser, and the optical bench;
8. the Committee has followed a development schedule based on guidance from the D/SRE Future Projects Office, constrained to an SPC adoption in early 2025, and a launch in 2034. With the successful start of LISA Pathfinder science operations, the Committee believes that its solid technical and scientific basis permits an earlier launch date if that could be decoupled from the present programmatically driven schedule. An earlier launch date would also improve the return from Europe's investment in industry and personnel;
9. the Committee's assessment is that there are no fundamental or conceptual issues with the data analysis. At the same time, it represents a challenge, both algorithmically and computationally. The momentum that had built up in the LISA/eLISA/NGO community has somewhat dissipated, with national funding generally no longer forthcoming, presumably due to the distant launch date. The Committee considers that this is a risk situation, and that it would be advantageous for certain data analysis activities to be resumed promptly, not least since some will impact on, and will guide, the technical design;
10. as exemplified by previous in-depth exercises, costs are only rather weakly dependent on system architecture. The Committee identifies some specific considerations but, as directed by ESA, did not embark on any new assessment;
11. from its inception, the former LISA mission was a productive collaboration among scientists in Europe and the US, striving to achieve the outstanding science promised by the L3 Gravitational Wave mission. The Committee suggests that such a mission will be more robust, and provide a greater science return per euro, if the US could consider a larger contribution, including a re-establishment of a meaningful collaboration. Currently this is restricted by funding in the US and ESA's provisional cost cap on non-European participation. The Committee has confidence that ESA can continue leadership in this new scientific frontier while encouraging a larger participation by the US;
12. the Committee has not been tasked with identifying or soliciting other international partners, and simply summarises the known status in Chapter 9.

Summary

As a result of its meetings, the analysis of requested inputs, and much detailed scientific and technical work by the gravitational wave community, the Gravitational Observatory Advisory Team (GOAT) can report to the ESA Executive in summary as follows:

- an L3 mission in gravitational waves is technically feasible, with laser interferometry between free-falling test masses as a well-established technical baseline;
- the scientific potential of a space mission in gravitational wave astronomy is compelling, and made more so by the recent Advanced–LIGO results;
- the technical and scientific knowledge base now residing in Europe as a result of LISA Pathfinder argues for the timely implementation of a gravitational wave observatory under European leadership.

The First Gravitational Wave Detection, Announced on 11 February 2016

What was observed?

• first evidence of gravitational waves through direct detection, 100 years after their prediction
• the most powerful astronomical event observed since the Big Bang
• two ~30 solar mass black holes, moving at half the speed of light, merging into a single entity

What is the significance of the LIGO–Virgo Collaboration discovery?

• it confirms Einstein's description of gravity in the strong regime, never directly tested before
• it confirms the overall simplicity of black holes, despite their complex environment
• it confirms that gravitational waves propagate unimpeded across the Universe
• it confirms that gravitational waves preserve the information at the time of their generation

What are the implications for the L3 mission?

• it demonstrates that laser interferometry can detect gravitational waves
• it strengthens the enormous and revolutionary scientific case for the L3 mission
• it demonstrates the discovery potential of the L3 mission
• it enhances ground-based gravitational wave and electromagnetic source detection

LISA Pathfinder Technology Demonstrator, Launched on 3 December 2015

What is LISA Pathfinder aiming to demonstrate?

• that two test-masses at the end of one L3 arm can be placed in free fall
• that the residual disturbances are at the levels required for embarking on L3
• that the space implementation of free falling bodies allows the prediction of L3 performances
• that free-fall is demonstrated using the same hardware likely to be used in L3

What has LISA Pathfinder demonstrated at the start of science operations?

• successful spacecraft and payload commissioning
• successful release and control of the free-falling test masses
• successful demonstration of picometre interferomertry between two free-falling test masses
• successful demonstration of drag-free satellite operation

What are the implications for the L3 mission?

• it provides flight demonstration of major components of the L3 space instrumentation
• it provides confidence in picometre interferometry between two free-falling test masses
• it demonstrates drag-free satellite operations necessary for a gravitational wave mission
• it will demonstrate that L3 can reach its intended free-fall performances

1 Introduction

1.1 Objectives of the Advisory Team

In 2013 the Director of Science & Robotic Exploration (D/SRE) tasked a Senior Science Committee to advise on the goals for the next 'large missions' (L2 and L3, for launch in 2028 and 2034 respectively). The SSC advised that L3 should address the theme 'The Gravitational Universe'.

In November 2013 the Science Programme Committee selected the theme 'The Gravitational Universe' for L3. Subsequently, D/SRE appointed a Gravitational Observatory Advisory Team to advise on the scientific and technological approach for a gravitational wave observatory for launch in 2034. The Committee's boundary conditions were specified as follows:

- L3 will be European-led, with a cost to ESA not to exceed 1 B€ (2014 economic conditions), plus an expected national contribution of order 25% of the ESA cost;
- international participation will be limited to elements not exceeding approximately 20% of the total mission cost;
- the mission must be based on technology that can credibly achieve Technology Readiness Level 6 (TRL 6, on the ISO scale; see p. 31) by the mission's adoption;
- the mission profile must be compatible with a 'Call for Mission' to be issued around the end of the present decade [although the present target of D/SRE is 2016 Q3];
- the mission must address the science goals in the Senior Science Committee report.

The objectives of the committee are:

- to identify promising technologies for the detection of gravitational waves from space and their use as 'astrophysical messengers' in the context of L3;
- to recommend on the technological activities and milestones needed to develop and eventually choose between the most promising technologies;
- to identify possible scientific and technological milestones that should be achieved (either by ESA or independently) and the relevant decisions linked to these milestones;
- to engage with the gravitational wave scientific community to ensure that the most recent information and promising approach are considered.

In the spirit of the Terms of Reference of the present activity, where a *scientific theme* rather than a *mission architecture* has been prescribed, the term 'L3 mission' is used throughout this report, instead of the acronyms LISA, eLISA, or NGO which convey a specific design solution.

1.2 Development history

The first ideas for detection of gravitational waves by long-baseline laser interferometry in space were presented 30 years ago at the Joint Institute for Laboratory Astrophysics (JILA), USA. Over this lengthy interval, various mission concepts have been formulated and studied in detail, marked by the following milestones:

1985 first mission concept (by J. E. Faller, P. L. Bender, D. Hils and M. A. Vincent), LAGOS (Laser Antenna for Gravitational-radiation Observation in Space): four drag-free spacecraft in heliocentric orbit, forming an interferometer with two arms separated by 120°;

1993 May LISA (Laser Interferometer Space Antenna) proposed to ESA by a European science team coordinated by K. Danzmann, in response to the Call for Mission Proposals for the third 'medium size mission' (M3) within the 'Horizon 2000' programme: four spacecraft in heliocentric orbit, forming an interferometer with a baseline of 5×10^6 km.

Similar objectives were addressed by a second M3 proposal, coordinated by R. W. Hellings. SAGITTARIUS consisted of six spacecraft in a geocentric orbit, to form an interferometer with a baseline of 1×10^6 km. ESA decided to merge the two missions for a common M3 assessment study, initially called LISAG, and later LISA;

1993 Dec with LISA not expected to meet the M3 cost envelope, it was proposed as a cornerstone project for 'Horizon 2000 Plus', as six spacecraft in heliocentric orbit;

1995 Horizon 2000 Plus officially announced, with LISA as the fourth 'cornerstone mission';

1997 Feb the LISA team and ESA's Fundamental Physics Advisory Group (FPAG) recommended to carry out LISA in collaboration with NASA. Several technical measures were introduced to reduce the overall cost of the mission, including in particular a reduction of the number of spacecraft from six to three, launched by a single Delta II vehicle;

1998 Nov publication of the pre-Phase A Report (2nd edition), summarising the results of the European study for the revised version of LISA with three spacecraft in a heliocentric orbit, in cooperation with NASA. The report took into account an independent Team-X study performed at JPL, basically confirming its feasibility;

1998 proposal for ELITE (European LISA Technology Experiment), a satellite mission to demonstrate dedicated technologies required for LISA;

1999 Jun industrial assessment study of LISA under ESA contract (final report in April 2000): a detailed spacecraft and subsystem design to identify implications of the selected instrument concept and predict the system performance;

2000 Nov the SPC approved SMART–2, a refined version of ELITE. SMART–2 was proposed as a joint LISA and Darwin pathfinder mission, consisting of two spacecraft with a European LISA technology package, a NASA-provided LISA technology package, and a Darwin technology package. After initial industrial study, the mission was descoped to a single spacecraft without the Darwin technology package, and renamed 'LISA Pathfinder';

2005 Jan the industrial LISA mission formulation study detailed all aspects of the LISA mission, trading off and consolidating the payload architecture. The concept of a triangular constellation, formed by laser interferometry over 5×10^6 km between three identical spacecraft, was maintained throughout the entire study. It was concluded in February 2011 with the Mission Consolidation Review;

2007 Oct LISA joined the ESA Cosmic Vision process, in competition with three other L mission candidates (EJSM–LAPLACE, IXO, and TandEM/TSSM), selected by the SPC;

2011 Apr in response to US decadal survey rankings of the L missions, as well as US budget constraints, ESA investigated the affordability of European-led L missions with only limited international participation, instead of proceeding with the L mission down-selection as planned in June 2011. Small industrial assessment studies were awarded for a reformulation of all three L missions, and in October 2011 a European only 'reformulation study' was performed by Astrium under ESA contract, with the support of the University of Glasgow for the optical bench. The scaled-down design was initially known as the New Gravitational wave Observatory (NGO) for the ESA L1 mission selection;

2012 May the SPC selected JUICE as the L1 mission, with a launch date of 2022. The gravitational wave mission was re-named eLISA (Evolved Laser Interferometer Space Antenna);

2013 Nov the SPC selected the theme 'the hot and energetic Universe' for L2 with launch in 2028, and the 'gravitational Universe' as the theme for L3, with launch in 2034;

2015 Dec 3 launch of LISA Pathfinder;

2016 Feb 11 announcement of the first detection of gravitational waves (Figure 1.1), from two merging $\sim 30 M_\odot$ black holes, by Advanced LIGO (Abbott et al., 2016).

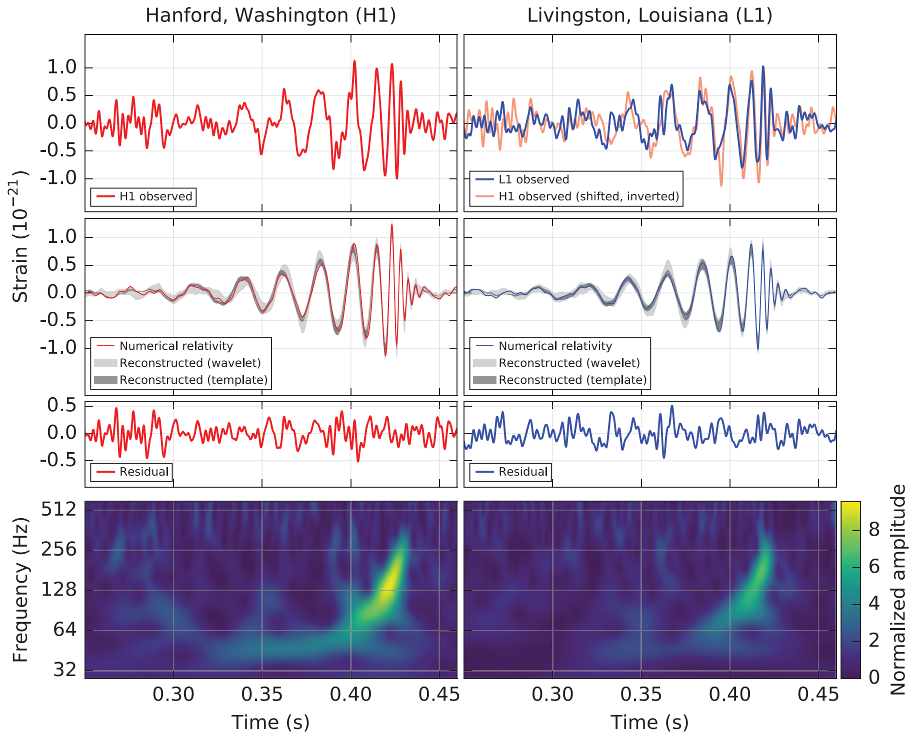

Figure 1.1: The first gravitational wave signals detected, by the twin LIGO stations, on 14 September 2015. The event, GW 150914, is attributed to the merger of two black holes, of masses $29 M_\odot$ and $36 M_\odot$, at a distance of 410 Mpc ($z = 0.9$). The signal began at a frequency of about 35 Hz, and rapidly increased to around 250 Hz, before dying down and disappearing within about 0.3 s of its appearance. The signal appeared first at the Livingston station, and at Hanford 7 msec later. From Abbott et al. (2016).

1.3 LISA Pathfinder

1.3.1 Objectives

LISA Pathfinder (formerly SMART–2) is a precursor mission to test the critical technologies needed for a LISA-like gravitational wave observatory, except for those required by the spacecraft-to-spacecraft interferometric laser ranging. Its primary goal is to test the feasibility of measuring geodesic motion to within an order of magnitude of the LISA/eLISA requirements, using specifically-designed hardware, thus representing an improvement of several orders of magnitude relative to any existing or planned mission using free-falling reference bodies (Vitale, 2012; Vitale et al., 2013).

To achieve its goals, LISA Pathfinder aims to measure the relative motion of two 2 kg test-masses in near-perfect geodesic motion by means of a picometer-sensitive laser interferometer. In contrast to LISA with its test masses separated by $\sim 5 \times 10^9$ m, the LISA Pathfinder test masses are 0.38 m apart in a single spacecraft.

LISA Pathfinder provides an experimentally-anchored physical model for all the spurious effects, including stray forces and optical measurement limits, that may affect the drag-free performance of the gravitational wave observatory.

In particular, the mission will verify and (depending on its degree of success, and with some caveats on lifetime aspects) will advance to TRL > 7:

- drag-free control of spacecraft with freely suspended test-masses;
- precision attitude and trajectory control of the spacecraft;
- low noise μN-thrusters to implement drag-free control;
- inertial sensors with large gaps, heavy masses and no mechanical contact to spacecraft (this includes a test-mass launch lock, plus a mechanism for the injection of test-masses into orbit with high positional accuracy and low momentum);
- high stability electrical actuation on orthogonal degrees of freedom;
- non-contact discharging of test-masses by ultraviolet illumination;
- relative motion of test-masses and spacecraft from picometer interferometry;
- high spacecraft thermo-mechanical stability (for low self-gravity noise);
- gravitational field control and cancellation;

The inertial sensors, along with the interferometer and associated instrumentation, are part of the 'LISA Technology Package', supplied by contributing institutions across Europe, and integrated by Airbus Defence and Space Germany. LISA Pathfinder will test two different thruster technologies using the inertial sensor in the LISA Technology Package: a European system using cold-gas microNewton thrusters (similar to those used on Gaia) in a dedicated configuration, and a US-built 'Disturbance Reduction System' with colloid-based thrusters.

1.3.2 Status

The spacecraft was launched on 2015 December 3 into an elliptical low-Earth orbit, from where successive perigee boosts raised the apogee closer to the intended halo orbit around the Earth–Sun L1 point. Subsequent milestones have been:

- 2016 Jan 12: switch on of the various payload elements, including the laser
- 2016 Jan 22: arrival at the target L1 orbit
- 2016 Feb 03: release of launch lock of the two test masses
- 2016 Feb 15–16: final release of test masses
- 2016 Feb 29: start of science operations

In its report of 7 March 2016, the In Orbit Commissioning Board concluded with the statement that... *"the requirements identified in the in-orbit commissioning specification have been fully met, giving confidence that the required science performance will be achieved."*

1.3.3 Evaluation of the scientific and technical performance

A careful evaluation of the scientific and technical performance of LISA Pathfinder will be a crucial element in moving forward with the L3 mission. The ESA Science Directorate currently plans to establish a separate body, towards the end of 2016, for this exercise. In broad terms, it would include individuals deeply involved in the mission along with independent external experts, and include appropriate NASA delegates. Once the data reduction is completed, this committee would make an independent assessment of the mission's results, performance, and outcome in the context of the L3 development planning and its TRL readiness.

Although nominally considered to start its activities towards the end of 2016, the precise timing will depend on the actual duration of the LISA Pathfinder mission, including any mission extension that might be authorised.

1.4 Laser Ranging Interferometer on GRACE Follow-On mission

The GRACE Follow-On mission will include an intersatellite Laser-Ranging Interferometer (LRI) to measure fluctuations in the separation between separated spacecraft by heterodyne laser interferometry. GRACE Follow-On is a joint US–German mission, and LRI is a collaboration between LISA partners from the AEI and JPL. The LRI will be the first long-distance interspacecraft interferometer; its design draws directly from LISA technology development and features LISA-representative received signal powers despite the much shorter 250 km baseline.

The LRI includes several technologies directly relevant for a LISA-like mission: quadrant photoreceivers, a phasemeter running LISA tracking algorithms in the presence of laser frequency noise, a master laser, and a laser frequency stabilisation capability that supports LISA requirements. Both the heterodyne frequency (MHz) and the measurement band (mHz) are comparable to those required for L3. The LRI also includes algorithms for initial acquisition of the laser link in a situation comparable to LISA. The first set of LRI flight hardware has been delivered to the spacecraft for integration.

During the design and test phase of the LRI, significant experience in long-distance interspacecraft interferometry has been gained, e.g. concerning photoreceivers, fiber optics, the phasemeter, frequency stabilisation, tilt-to-length coupling mechanisms etc. GRACE Follow-On is scheduled for launch in August 2017.

2

Scientific objectives

2.1 Introduction

The scientific objectives of LISA/eLISA/NGO have been presented in depth elsewhere (e.g. Schutz, 2011; Amaro-Seoane et al., 2012, 2013; Schutz, 2014; Stebbins et al., 2014; Danzmann, 2015). Here, we provide a concise summary, and focus on those aspects that are relevant for an understanding of the implications for mission performance, configuration trade-offs, and data analysis.

The sensitivity curves predicted for a long armlength laser interferometry mission in space (Figure 2.1) are such that many thousands of gravitational wave sources should be detectable at high signal-to-noise, and in many cases (extremely) well characterised in terms of frequency, position on the sky, and luminosity distance.

Detailed simulations of plausible instrument configurations (Chapter 4) shows that there are three main classes of astrophysical sources that should be detected: close compact binaries in our Galaxy [the vast majority are compact white dwarf binaries (CWD), but binaries comprising one or more neutron stars or black holes are of special interest], extreme mass ratio inspirals (EMRI), and massive black hole binaries (MBHB). Stochastic backgrounds of gravitational waves, of primordial or astrophysical origin, might also be detected. From the survey of many individual sources, the scientific themes addressed by the L3 mission will focus on:

- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

Figure 2.2 indicates how these science topics are related to the detection of the various sources. Figure 2.3 shows the detectability of sources as a function of observational frequency and, correspondingly, instrument. It illustrates that a gravitational observatory in space offers the most rewarding bandwith, with an abundance of astrophysical sources.

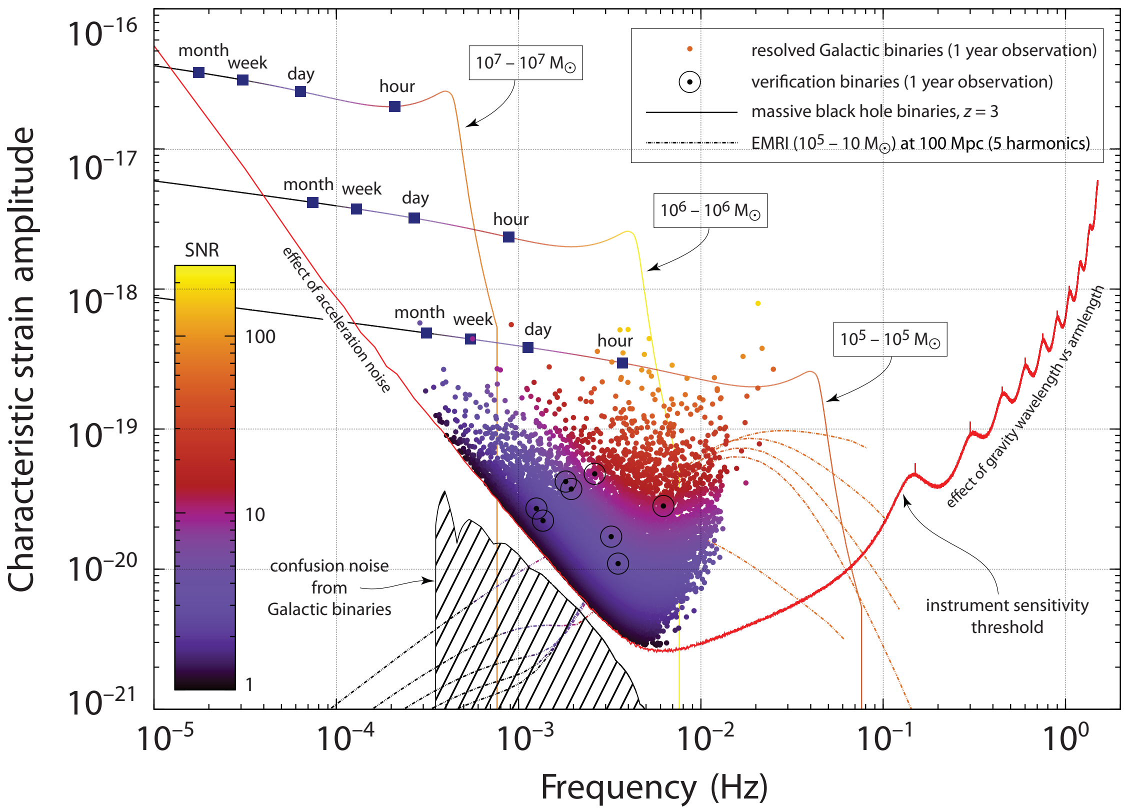

Figure 2.1: Characteristic strain amplitude, $\nu\, h(\nu)$, versus frequency for a space-based laser interferometry mission (armlength = 1×10^6 km, 1-yr observations). Objects expected to be strong gravitational wave sources over this frequency range are indicated. For compact white dwarf binaries, individual simulated sources, known 'verification binaries', and the effect of confusion noise from the ensemble of fainter sources, are shown. Dashed lines give example loci for extreme mass ratio inspirals (EMRIs) for the case of a $10^5 M_\odot - 10 M_\odot$ binary (and showing the 5 strongest harmonics). Solid curves show three example loci of massive black hole binaries of different mass, labelled with the time intervals over which the source remains 'in band'. In all cases, colour coding shows the corresponding (cumulative) S/N, increasing toward higher frequency as each system becomes more compact (this version courtesy Stas Babak, AEI, and Antoine Petiteau, APC).

Figure 2.2: The contribution of the different astrophysical sources detected by the mission to the various scientific topics.The intensity of shading is intended to give some general indication of the relevance of the sources to the topics addressed.

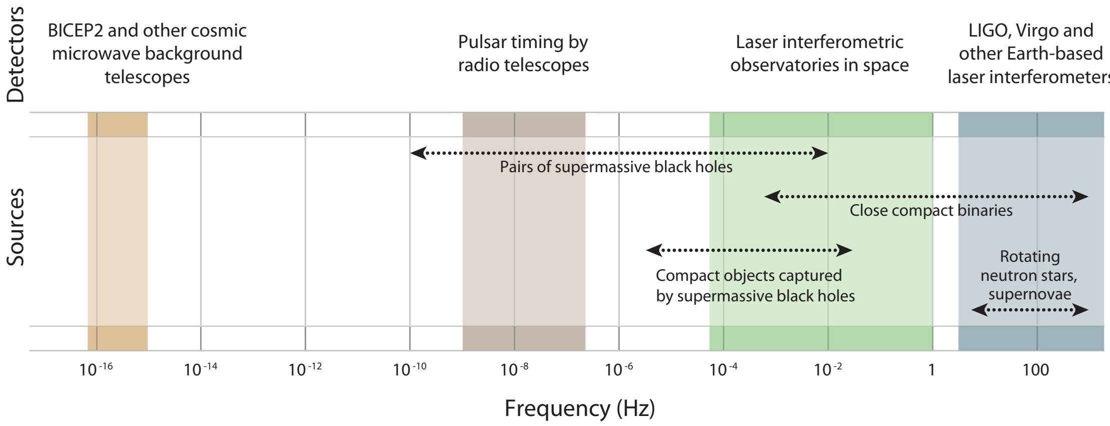

Figure 2.3: Frequency range of gravitational wave sources and bandwidth of corresponding gravitational wave detectors on Earth and in space. A gravitational wave background generated during cosmic inflation should be present over the entire frequency spectrum. From Barke et al. (2015), Classical and Quantum Gravity, Volume 32, article 095004, Fig 1 (courtesy Simon Barke).

2.2 Classes of sources

We first comment briefly on each of the classes of sources which will drive the mission science.

2.2.1 Compact white dwarf binaries (CWDs)

The large population of white dwarf binaries in our Galaxy emits gravitational waves across the whole LISA/eLISA band. There are predicted to be of order 10^7 Galactic binaries, the vast majority of which will not be individually resolvable, and which will therefore create a stochastic gravitational wave foreground below 3–5 mHz. Some Galactic binaries are known from electromagnetic observations (others will probably be provided by Gaia). Some dozen of these are guaranteed LISA/eLISA sources, and therefore referred to as 'verification binaries'. Depending on the particular satellite configuration adopted, some 1000–10 000 are expected to be individually resolved and characterised (Table 4.1). Each signal is long lived, and almost monochromatic, with just a small drift in frequency (due to gravitational wave emission or/and due to mass transfer). Each signal is characterised by 7–8 parameters, depending on whether the frequency drift is measurable. Expected signal-to-noise ratios are typically moderate (up to about 100). A sample population of white dwarf binaries is shown as dots in Figure 2.1, among which the verification binaries are shown as circles.

2.2.2 Compact neutron-star and black-hole binaries

The recent first detection of gravitational waves by LIGO suggests that there may be a large population of stellar-mass black-hole/black-hole binaries of significant total mass ($> 50M_{\odot}$). Individual systems at modest redshifts could be detectable by LISA/eLISA and then in a few years again by a ground-based system, with a potentially rich return on science from such a joint observation. The implications for LISA/eLISA are currently being studied in the community, and we discuss this in more detail in Section 2.4. When LIGO begins to detect neutron-star/neutron-star and neutron-star/black-hole systems it will be important to re-evaluate whether they will contribute significant new science in the LISA/eLISA band.

2.2.3 Massive black hole binaries (MBHBs)

These sources trace the ongoing mergers of massive black holes at the centre of galaxies, when these galaxies are merging. Their numbers and form will establish the cosmological merger history of this important population, and will help to establish what is the role of these central massive black holes in the dynamics of galaxy formation and evolution. These systems are expected to generate some of the strongest signals that low-frequency gravitational waves telescope can detect: they provide what can be considered as the gold-plated events of gravitational astronomy. In many cases, component masses and black hole spins, as well as distance and sky location, can be established from the gravitational wave profiles (Figure 2.4).

2.2.4 Extreme mass ratio inspirals (EMRIs)

These are systems in which an object orbits a much more massive object (factor $\gtrsim 10^4$). The orbit gradually decays through the emission of gravitational waves. Such systems are likely to be found in the centers of galaxies, where stellar mass compact objects, such as stellar black holes and neutron stars, may orbit a supermassive black hole. These systems evolve slowly over many thousands of cycles before eventually plunging, with the gravitational wave signal encoding a precise map of the spacetime geometry of the supermassive black hole (Figure 2.5). Simulations suggest that the most performant (LISA-like) configurations may detect some 5000–10 000 systems. For each, observations will allow accurate determination of the system parameters.

2.2.5 Gravitational wave backgrounds

Backgrounds of gravitational waves will also be searched for by the L3 mission. These backgrounds could be of astrophysical (such as the background of unresolved compact white dwarf binaries) or cosmological nature. One important issue is how to disentangle such backgrounds from the instrumental noise. The symmetry of the 6-link version of the mission provides a mode that suppresses the signals, and thus gives access in flight to the instrumental noise (Hogan & Bender, 2001). In the case of a 4-link mission, a study is presently being conducted to see how one could proceed to achieve the same goal through the knowledge of some of the characteristics of the instrumental noise (Adams & Cornish, 2010, 2014).

2.3 Science topics

The detection of the various sources and backgrounds allows significant progress in the understanding of the following science themes:

2.3.1 The nature of gravity

Gravity is the least precisely known of all the fundamental interactions, and we know that general relativity, successful as it is, must have corrections at some level where the effects of a quantum theory of gravity become sensible. Gravitational wave observations have the potential to perform strong tests, many of them unique. Binary systems of black holes are a particularly good place to test gravity because (a) the systems are simple to model (no complicating gas dynamics) and (b) in the merger of black holes we see the strongest possible gravitational fields. LIGO, with its very first observation, has already shown the potential for this kind of test. Its detected waveform from the merger of two black holes agrees with detailed numerical simulations done in full general relativity to the full accuracy of about 5% allowed by the signal-to-noise ratio of the detection (24). The waveform also contains a hint of the ringdown of the final merged black hole, which is the first observation of the dynamics of a black hole. Finally, LIGO has been able to set an upper limit on the mass of the graviton of 1.2×10^{-22} eV from the fact that there is no observable frequency dispersion in the signal as it propagated 0.4 Gpc from the source to the detector.

With more observations, LIGO and Virgo and the other ground-based detectors expected in Japan and India will be able to improve these limits and also test for additional polarisation states; but these tests will probably not go much beyond the 1% level. Impressive as this is, any deviations of the true theory of gravity from general relativity are likely to be smaller than this, coming potentially from the quantum gravity/string theory regimes. A space mission will observe merging black holes with S/N 100 times larger than LIGO can, and at redshifts of 10–15 rather than LIGO's 0.1. Much more stringent tests can therefore be expected across all aspects of gravitation theory:

- the nature of gravity in weak and strong field regime,
- the nature of black holes (see next subsection),

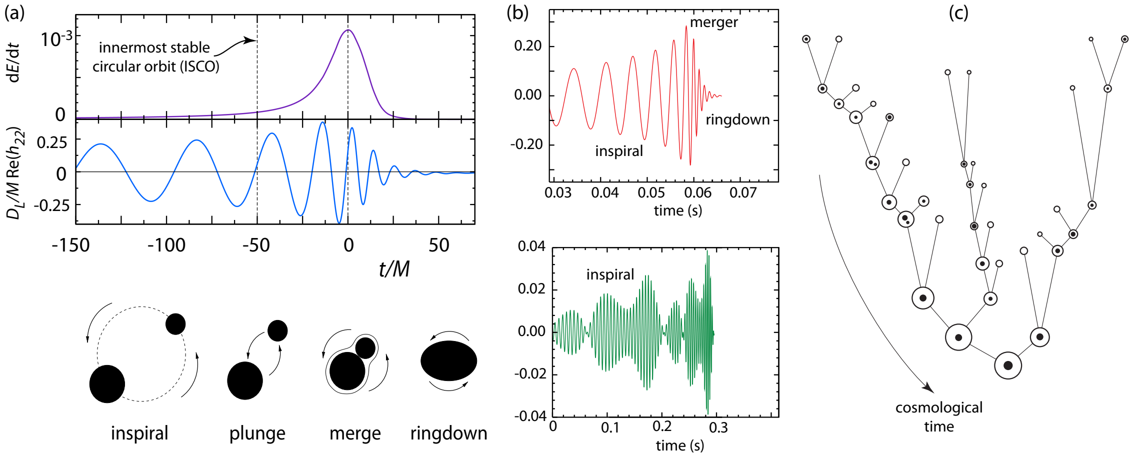

Figure 2.4: Gravitational wave signals from massive black hole binaries (MBHBs): (a) gravitational wave energy (upper) and generic waveform (lower) for a massive black hole binary system illustrating the successive inspiral, plunge, merge, and ringdown phases; (b) two simulated waveforms, illustrating how the waveforms are highly sensitive to the binary system parameters, including the mass and spin of each component, as well as the detailed orbit geometry; (c) in the currently favored cosmological model, galaxies form in a hierarchical fashion, starting from small systems at early times, and then growing via mergers: each galaxy observed today is a consequence of its merger history extending back to high redshifts. If black holes formed at early times, they will have followed the merger hierarchy of their host galaxies. Black hole mergers are therefore expected to be common events.

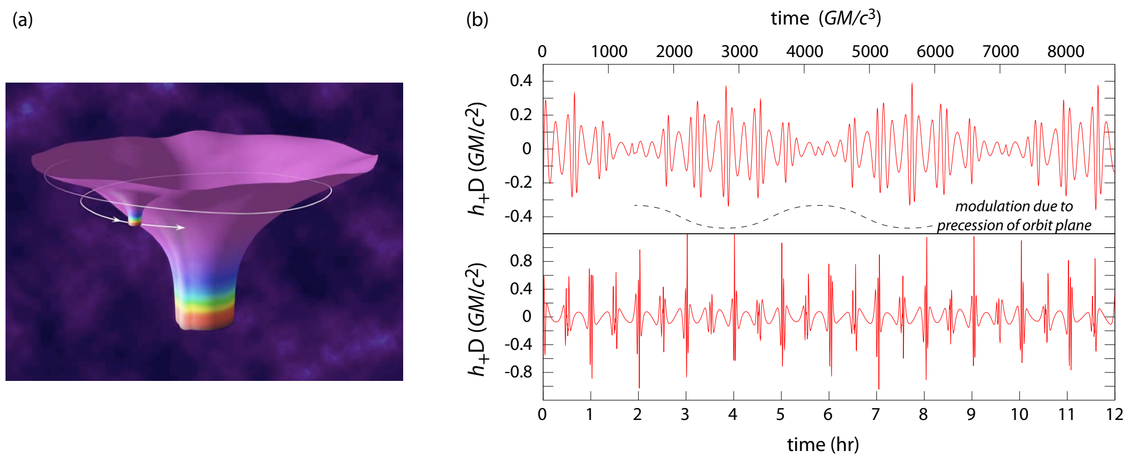

Figure 2.5: Gravitational wave signals from 'extreme mass ratio inspiral' systems (EMRIs): (a) schematic of the associated spacetime (Drasco & Hughes, 2006; Amaro-Seoane et al., 2013); (b) segments of generic waveforms, showing the plus-polarised waves produced by a test mass orbiting a $10^6\,M_\odot$ black hole spinning at 90 per cent of the maximal rate allowed by general relativity, at a distance D from the observer (Drasco & Hughes, 2006; Amaro-Seoane et al., 2013). Top panel: slightly eccentric and inclined retrograde orbit modestly far from the horizon, in which the amplitude modulation is mostly due to Lense–Thirring precession of the orbit plane. Bottom panel: highly eccentric and inclined prograde orbit closer to the horizon, in which the more eccentric orbit produces sharp spikes at each pericentre passage.

- propagation effects, such as constraining the graviton mass,
- the existence of extra polarisations.

2.3.2 The fundamental nature of black holes

Black holes are the most striking prediction of Einstein's general relativity and they offer unique possibilities for testing the theory for two reasons: (a) they have the strongest gravitational fields we can access; and (b) they are extraordinarily simple and accurate to model: the Kerr metric, which describes all stationary black holes in the universe, is fully specified by just two numbers, the mass and spin of the black hole. As described in the previous subsection, LIGO's very first observation already provided strong confidence in the general relativity description of black holes. Observations from a space-based gravitational wave observatory will improve on these, and provide further tests unique to space (Hopman & Alexander, 2006; Preto & Amaro-Seoane, 2010; Hopman & Alexander, 2005; Lodato & Natarajan, 2006; Berti et al., 2007; Petiteau et al., 2011).

One good EMRI event should allow a test of the existence of a horizon around black holes by identifying the sudden extinction of the signal when the small compact object falls into the horizon. It will also be possible to test the hypothesis, to high accuracy, that the central object is indeed a supermassive black hole, by measuring the quadrupole moment of the gravitational field to an accuracy of a fraction of a percent. More generally, the mapping of the horizon region provided by the many cycles of a compact object around the supermassive black holes should provide key information on the properties of this black hole, especially on its Kerr nature. The final phase (ringdown) of the massive black hole coalescence (MBHB) provides key tests of the 'no-hair theorem', according to which a black hole is defined by three numbers (charge, spin and mass): the system of two black holes sheds its superfluous properties after coalescence through gravitational wave emission.

In summary the mission will probe:

- the existence and nature of the black hole horizon
- tests of the Kerr nature of black holes (black hole mapping)
- ringdown tests of the no-hair theorem (black hole spectroscopy)

2.3.3 Black holes as sources of energy

The (gravitational wave) luminosity of an event such as a massive black hole merger is some 10^{23} orders of magnitude larger than the Sun (electromagnetic) luminosity. If even a very small fraction of this energy is converted into electromagnetic waves, this provides an electromagnetic counterpart to this event. A key issue is however timing: gravitational waves emerge rapidly whereas electromagnetic signals may be delayed by diffusion in the material background of the black hole.

In summary the mission will probe:

- the formation of jets, the Blandford–Znajek effect, and the radio loud/quiet dichotomy
- tests of accretion disk models
- transient counterparts (from prompt to month scales)

2.3.4 Nonlinear structure formation

In the currently favoured scenario for the formation of cosmic structures in the Universe, present-day galaxies have been built up, via a series of mergers, from small building blocks that formed at earlier cosmic times. Galaxies experience multiple mergers during their lifetime. A single large galaxy, now containing a massive black hole, can be traced back to the stage when it was split up in hundreds of components with masses a million times smaller than today's galaxies. The properties of the black hole population observed are given by the combination of their birth rate, merger rate, and growth rate of each black hole though accretion of matter. The mass and the frequency of the seeds, as well as the dynamical evolution of black hole pairs, ultimately dictate the distribution of massive black holes in galaxies.

In summary the mission will probe (Klein et al., 2016):

- the seed formation (at high redshift),
- the hierarchical assembly (at mid-to-low redshifts),
- models of accretion (coherent vs chaotic).

2.3.5 Dynamics of galactic nuclei

It is important to understand the dynamics of the galactic nuclei in order to predict accurate rates for EMRI events. But conversely, the detection of EMRI events will provide key information on the stellar dynamics and content of the inner region of a few 0.01 pc around the galactic nucleus. For example, the distribution of eccentricities of EMRI events might give precious information on the stellar formation in accretion disks and on the tidal disruption of binary systems (two distinct sources of compact remnants in the vicinity of the central black hole).

In summary the mission will probe:

- the low mass end of the massive black hole mass function,
- the relaxation and EMRI formation channels,
- the mass segregation and black hole mass functions in galactic nuclei,
- the relativistic dynamics, for example the Schwarzschild barrier.

2.3.6 Formation and evolution of stellar binary systems

A gravitational wave mission will provide scientific insight into the number of ultra-compact binaries in the Galaxy, as well as the merger rate of white dwarfs, neutron stars, and stellar mass black holes in the Galaxy: this will thus better constrain the rate of their associated explosive events. It will allow to study the onset of white dwarf mass exchange events with another white dwarf or neutron star, and the consequences for the explosion mechanism of Type Ia supernovae. Moreover, it will give access to the spatial distribution of ultra-compact binaries, and what this reveals about the structure of our Galaxy as a whole.

The mission will thus probe:

- the formation of compact object binaries
- the nature/physics of white dwarf mergers
- the structure of the Milky Way

2.3.7 The very early Universe

The L3 mission may provide significant information on epochs of the evolution of the Universe which precede the Hydrogen recombination era when the photons of the CMB were produced. Indeed, the frequency window correspond to the epoch when the energy density of the Universe is $0.1-10^3$ TeV: at these energies, we expect the occurrence of the electroweak phase transition and possibly of phase transitions related to physics beyond the Standard Model. There is thus a nice complementarity with LHC and foreseen higher energy colliders. For the gravitational waves to be detected, the phase transition has to be violent enough (i.e., strongly first order). Other potential cosmological backgrounds are those due to networks of cosmic strings (associated with phase transitions or fundamental superstrings) or those related with inflation. In the simplest models of inflation, however, primordial gravitational waves are too low to be detected with the sensitivity of the detector foreseen.

In summary the mission will probe (Caprini et al., 2015; Caprini et al., 2016):

- Higgs physics and beyond, and multi-TeV physics
- topological defects, in particular cosmic or fundamental strings
- nonstandard inflation and related phenomena (reheating, etc.)

2.3.8 Cosmography

Some of the events identified by the mission (MBHB, EMRI) provide a very different (i.e. gravitational) way of measuring the luminosity distances of far away events, thus leading to new means of identifying cosmic distances through what are called *standard sirens*, in reference to the analogy of gravitational waves with sound waves. For this method to be successful, one needs to identify the redshift, either with an electromagnetic counterpart or through statistical identification of the host galaxy in the detection window. The advantage of this method is to provide precise determination of cosmological parameters, e.g. the dark energy equation of state parameter, based on a direct measurement of the luminosity distance up to large redshift, unlike optical measurements which require cross-calibrations of successive distance indicators at different scales. Similarly, clustering of galaxies allows extraction of the redshift information from a statistical sample of EMRI events which is expected to allow precise determination of luminosity distance, providing an independent way of determining the Hubble parameter at cosmic distances (MacLeod & Hogan, 2008).

In summary the mission will probe (Caprini et al., 2016; Tamanini et al., 2016):

- the Hubble constant to a few percent accuracy
- the equation of state of dark energy to a few percent accuracy

2.4 The discovery of gravitational waves: expected consequences for L3 science

The discovery of gravitational waves announced by the LIGO and Virgo collaboration (Abbott et al., 2016) has confirmed the existence of these waves. It has also led to the discovery of a first merger of a binary system of black holes. These are important confirmations for the science of the L3 mission which reinforce its astrophysical importance, and its timeliness.

This does not preclude any of the scientific aspects of the L3 mission which, for the main part, observes other types of astrophysical sources, or the same sources (for example cosmological backgrounds) but in a different frequency window.

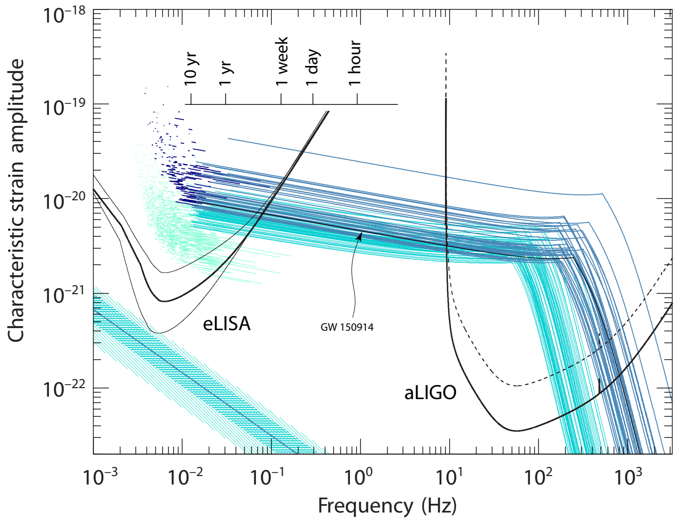

Figure 2.6: Gravitational wave signals from a heavy stellar black hole binary as discovered by the LIGO–Virgo collaboration. Violet lines are total sensitivity curves of three eLISA (2-arm) configurations with 1, 2, and 5 Mkm arm length (top to bottom). The U-shaped curves to the right are current (dashed) and design (solid) aLIGO sensitivity curves. Different blue shades represent characteristic amplitude tracks of BHB sources for a flat population model with S/N>1 in the 2 Mkm arm-length configuration (highlighted as the thick eLISA middle curve), integrated over a 5-yr lifetime. Light turquoise lines around 0.01 Hz are sources seen in eLISA with S/N<5; light and dark blue curves crossing to the aLIGO band are eLISA sources with S/N>5 and S/N>8 respectively; dark blue points in the upper left corner are other eLISA sources with S/N>8, but not crossing to the aLIGO band within the mission lifetime. For comparison, the characteristic amplitude track completed by GW150914 is shown as a black solid line. The scale at the top of the figure indicates the frequency progression of this particular source in the last 10 years before coalescence. The shaded area at bottom left is the expected confusion noise level produced by the same population model (median, 68% and 95% intervals are shown). From Sesana (2016).

The discovery of a binary system of stellar black holes with masses larger than expected has significantly enriched the scientific potential of the mission: the binary source observed by the LIGO detector was present for years in the L3/LISA frequency band, and disappeared from it only a few weeks before reappearing in the LIGO band for the final plunge (Sesana, 2016, see also Figure 2.6). The L3/LISA signal would allow prediction of the LIGO event, both in time and in source direction, with an accuracy that will allow electromagnetic observations of the merger itself in parallel with the LIGO observations.

This population of massive stellar black holes is thus a new type of source for the L3 mission. As evident in Figure 2.6, some of these sources can be seen by both space and ground detectors, whereas others may never reach the high frequencies of ground-based detectors in a human lifetime. This also leads to a background of unresolved sources which appears to lie ouside the LISA sensitivity curve for most configurations.

In the coming months and years, with more data from the LIGO (and Virgo) detector, there will be a better knowledge of the expected population of such sources, and thus more refined estimates. But, already, we have a striking example of the type of multiwavelength analysis that will be possible with the simultaneous functioning of space and ground detectors.

Such phenomena will lead to unprecedented constraints on many aspects of the fundamental physics of gravity (Barausse et al., 2016). This might also give rise to new observational strategies: the presence of these sources in the L3 band allows alerts to be issued for the electromagnetic observations *months in advance*, while their presence in the frequency range of both space and ground detectors may be used for cross-calibration.

3

Detection technologies

3.1 Survey of available techniques

The Committee has reviewed the various technologies proposed for the detection of gravitational waves using literature searches over the past 50 years, and compared these with the world-wide progress on these approaches where reported. The aim was to identify technologies relevant to the achievement of the science objectives outlined in the Senior Survey Report. That is to say, in broad terms, the ability to achieve a sensitivity in dimensionless amplitude, within one year, of 10^{-23} over the frequency band from 100 micro-Hz to 100 milli-Hz, referred to as the L3 band.

In total, 28 distinct technologies for registering the presence of a gravitational wave were identified (and are listed in Appendix B). Identified techniques fell into four categories: many were too insensitive to detect the dimensionless amplitude required; others only operated at frequencies outside the band of interest (either higher or lower); a further group were frequency independent, but lacked published studies quantifying their sensitivity levels over the L3 band.

The final category comprised the only two technologies which the Committee focused on as having the potential to meet the scientific requirements set by the Senior Survey Report: laser interferometry and atom interferometry.

3.2 Laser interferometry

Laser interferometry has been in operational use in gravitational wave detectors on ground since the 1970s. Instruments now in operation such as Advanced LIGO, Advanced Virgo and GEO 600 have already demonstrated the ability to read out test mass positions to somewhere below 10^{-19} m $Hz^{-0.5}$ at frequencies around 100 Hz. Most of the critical subsystem technology required for drag-free control has also been thoroughly developed for the LISA Pathfinder mission, by institutes in Europe and the US. The benefits from the operational experience gained during the LISA Pathfinder mission will also be available to those designing L3.

In addition, the Laser Ranging Interferometer on GRACE Follow-On will demonstrate inter-spacecraft laser interferometery in part of the LISA band using elements inherited from LISA technology development efforts in Germany and the US. GRACE Follow-On is scheduled for launch in August 2017.

3.3 Atom interferometry

3.3.1 Current status

Atom interferometry is currently under development in laboratory and demonstration versions. Ultra-cold neutral atoms provide excellent clocks (optical frequency metrology), and have the potential to be used as gravitational proof masses (through atom interferometry). Combination of these attributes could in principle enable a single baseline detector for gravitational waves (with corresponding limitations on sky position and polarisation information). First results date from the 1991 demonstration of an atom interferometer gravimeter. From a system perspective, the most recent concept envisages clouds of $\sim 10^8$ atoms which are extended over several cm, 'fly' for 10–100 s, need to be shielded from solar radiation, and then have their phase retrieved by momentum transfer imposed from the other spacecraft.

Recent publications have given outline descriptions and preliminary noise budgets for a space-based detector capable of achieving the L3 mission objectives, but no detailed studies of implementing such technology on a space platform have been completed.

The Committee has concluded that laser interferometry indeed offers demonstrated sensitivity on ground, as well as advanced preparation and demonstrated feasibility, for a space mission. No other technology has such an advanced technological status, and we focus on it exclusively in the rest of this report.

3.3.2 ESA Announcement of Opportunity for new science ideas

On 2016 February 9, the Director of Science issued an Announcement of Opportunity, soliciting from the broad scientific community proposals for the competitive selection of new 'Science Ideas', to be investigated in terms of feasibility and needed technology developments (`www.cosmos.esa.int/web/new-scientific-ideas`). The call aims at stimulating the emergence of new and innovative science ideas based on technologies not yet sufficiently mature, possibly to become potential candidates for future M or L missions in the ESA Science Programme.

The Committee considers that this call is well timed for nurturing the prospective Atom Interferometry concept. Thorough evaluation will allow this option to be assessed in parallel with the early phase of the L3 development cycle. The schedule announced calls for a Letter of Intent to be submitted by 2016 May 9, a briefing meeting at ESTEC on or around 2016 June 8, a proposal submission deadline of 2016 September 14, and a selection of proposals for study at the end of 2016.

4

Scientific performance trade-off

4.1 Instrument configurations assessed

To formulate a technology development strategy, an instrument design must be specified. However there will be boundary conditions that may prevail at the time of adoption that are unknown or at least somewhat uncertain today, including national contributions, international partners, cost analysis models, launcher options, and others.

Rather than adopt some configuration *a priori*, we have considered the most important parameters that characterise a laser interferometry mission (Figure 4.1), and obtained the support of the L3 scientific community to assess the associated scientific performances. We adopted the following range of parameter choices:

- armlength (satellite separation): 1×10^6 km, 2×10^6 km, 5×10^6 km. The sensitivity to *long wavelength* gravitational waves improves with increasing armlength, although at the expense of a small number of (relatively minor) architectural and design aspects;

- mission duration: 2 years or 5 years;

- low-frequency acceleration noise, corresponding either to the original LISA requirement (i.e. 10× better than the LISA Pathfinder goal), or to a factor 10 degradation;

- number of laser links: either 6 laser links between the three spacecraft (the original LISA configuration), or 4 links (as in the mother–two daughter design of the descoped NGO).

This gives a total of $3 \times 2 \times 2 \times 2 = 24$ configurations spanning a wide range of possible instrument configurations. For reference, the main attributes of LISA and NGO were as follows:

LISA (ESA–NASA): 3 spacecraft (6 links); orbit: heliocentric, tilted 60°, 20° Earth trailing, $D = 5 \times 10^9$ m; lifetime: 5-yr; test mass: cubes, two per spacecraft; thrusters: Cs FEEPs (ESA), colloidal (NASA), with cold gas (300 kg) as potential backup by ESA; telescope: $d = 0.4$ m (initially on-axis, later Astrium recommended off-axis), pm stability required; laser: 1 W end of life between spacecraft (2 W initial source power); launch: Atlas V (directly into escape orbit).

eLISA/NGO (ESA-led): 3 spacecraft, 4 links (one mother, two daughter); orbit: $D = 10^9$ m in drift away orbit (from 9 to 22°); lifetime: 2 yr; launcher: two Soyuz. Both the reduced nominal lifetime, and the reduced armlength, affected the predicted scientific return.

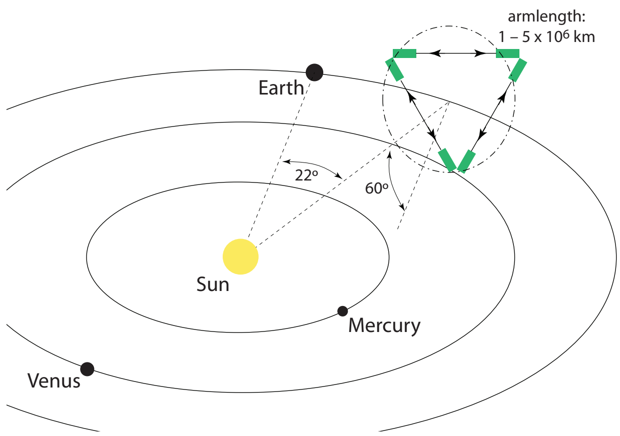

Figure 4.1: Schematic of the satellite and orbit configuration. The three satellites comprising the interferometers are in a heliocentric orbit which trails the Earth by 22°. By a very specific choice of the satellite orbits (in inclination, eccentricity, longitude of ascending node, and argument of pericentre), the three-satellite constellation rotates by 360° per year in inertial space.

4.2 Simulation results

The above parameter cases were passed to a dedicated consortium of scientists from 8 European and US institutes involved in developing the LISA/NGO simulation and data processing tools (details are listed in Appendix A). Further work was done by the scientific working groups of the eLISA consortium. They all reported back to the committee: this is summarised in the detailed results of their performance assessment for the 24 configurations given in Section 4.1.

Tables 4.1, 4.2, and 4.3 summarise the results in tabular form ('?' indicates ongoing work which is not yet conclusive, while '–' indicates that no estimate exists yet).

A detailed inspection of these tables demonstrates that viable science can be obtained from any of the configurations. The recent detection of gravitational waves has provided increased confidence that there is a richness of science in the gravitational wave sky. Accordingly, L3 would benefit quantitatively from something more than the *minimal configuration* in the context of a gravitational wave mission operational in the 2030s.

The simultaneous presence of 6 links allows the search for stochastic background signals by virtue of a better determination of the instrumental noise level using a symmetric combination of signals (Hogan & Bender, 2001). Most importantly, the 6-link configuration permits the simultaneous determination of the two polarisation states of each individual gravitational wave event. There are two source types which must be considered separately:

- this configuration is less critical in the case of white-dwarf binaries and EMRIs, which remain in the detectable frequency band for more than a year, and for which the polarisation degeneracy is broken by the orbital motion of the 3-spacecraft constellation. In this case, the improvement brought by 6 links compared with 4 links is basically related to an improvement in signal-to-noise. Accordingly, the detectable number of EMRIs increases by a factor 2.8 ($2^{3/2}$), and their parameter estimation accuracy improves by a factor 1.4 ($2^{1/2}$). The number of resolvable white-dwarf binaries increases by a factor $2^{1/2}$, and their parameter estimation accuracy improves by a factor 2;

- the gains are of more crucial importance for the strongly time-varying gravitational wave sources, such as massive black hole binaries, where the final merger occurs over weeks or days, and where the time-evolution of the polarisation is of substantive diagnostic power. In this case the mass and spin measurements have an improvement consistent with the increase in signal-to-noise going from one to two interferometers, i.e. an approximate factor of 1.4. Simulations indicate that mean distance estimates improve by roughly a factor 5, while the mean solid angle positional constraints improved by about 30 (Klein et al., 2016). This in turn implies, for example, that more than 10 times as many sources are constrained to better than 10 $\deg^2$ (from 1 per yr to 10 per yr), a gain of importance for the comparable fields of view of LSST and SKA, with their capability of detecting electromagnetic radiation from a $10^6 M_\odot$ black hole at $z \sim 2-3$.

Comparing the performances of the 2-arm/4-link configurations with the 3-arm/6-link configuration, the simulations demonstrate that a significant part of the scientific programme would be lost, or only partly achievable, in the case of the former.

From the point of view of mission lifetime, a duration of only 2 years significantly restricts the science reach of the gravitational wave observatory. For example, when using standard 'sirens' for cosmology (Section 2.3.8), it might be expected that the precision increases as $\sqrt{N}$ with the number of sources, and hence that the errors might increase by $\sqrt{5/2}$) going from a 5 year to a 2 year mission. On the contrary, simulations demonstrate that the loss is much more significant, because parameter degeneracies in the cosmological models are often broken only through the detection of a sufficient number of independent sources (Tamanini et al., 2016). The field of cosmography appears essentially lost in going from 5-year to a 2-year mission (compare Table 4.2 and 4.3).

Very short arm lengths, of order 1 Mkm or less, substantially restrict the scientific grasp. For example, the number of EMRIs expected falls by a factor of about 20 when going from 5 Mkm to 1 Mkm, while the number of MBHB localised to better than 10 $\deg^2$ is decreased by a factor of 5–10.

High levels of acceleration noise are particularly damaging for the science for the minimal configurations (see for example the first column of Table 4.2), although less so for the more extended versions.

Finally, the new science that can be envisaged after the discovery of GW150914, and the foreseen interplay between the space observatory and ground-based detectors (discussed in Section 2.4), reinforces these conclusions. For example, a 6-link mission with 2 Mkm arm length allows the *joint observation* of more than 50 resolved stellar black hole binaries by the L3 space observatory and ground-based detectors (with the possibility of alerts for the observation of electromagnetic signals), as well as the detection of the unresolved background with S/N larger than 30 (Sesana, 2016).

4.3 Architectural implications of mission configuration choices

This section provides a high-level summary of the impacts of the system configurations simulated in Section 4.2 on the flight hardware, in the context of cost, complexity and risk. The acceleration noise was not considered in the context of its hardware impact, with the drag-free performance traced to LISA Pathfinder taken as input.

4.3.1 Number of links

The principle considerations related to the number of arms (and links) are as follows:

- 6 links (3 identical satellites) provides mission redundancy against single-link component failure (e.g., a single inertial sensor), a consideration viewed as a compelling advantage;
- 4 links (1 mother, 2 daughter option) requires fewer total copies to be built and saves mass, but requires development and qualification of all elements of the 6 link design;
- 4 links requires engineering development and qualification of two specific hardware configurations (mother and daughter) compared to the symmetric 6-link design case.

From a scientific perspective:

- the simultaneous presence of 6 links allows the search for stochastic background signals through cross correlation;
- the 6 link configuration permits the simultaneous determination of the two polarisation states of each individual gravitational wave event.

4.3.2 Arm length

For shorter arm lengths:

- smaller 'breathing angles' simplify the point ahead mechanism and telescope pointing;
- Doppler shifts (which sets the photoreceiver and phasemeter bandwidth) are reduced;
- less propellant (and time) is required to achieve the final science configuration;
- longer mission durations follow from the reduced orbit perturbations.

For longer arm lengths, there are (perhaps less intuitively) no major technology development drivers for the options studied.

4.3.3 Lifetime

The principle considerations related to the mission lifetime are as follows:

- additional operations have associated costs but do not change the mission architecture;
- longer lifetime has added technology burdens (component and mechanism lifetimes);
- extended reliability associated with (say) a 5-year mission are real, but hard to cost;
- longer lifetime requires higher stability constellations:
  - a 5-year, 5 Mkm orbit would require additional propellant for injection into a longer lasting constellation;
  - some shorter duration, shorter separation missions can be optimised for mass using, e.g. a drift-away configuration.

4.4 Conclusions on the scientific performance tradeoff

The Committee finds that the minimum architectural configurations studied may be scientifically viable. However, the improved reliability and science performance of three identical spacecraft, and the enhanced scientific return of a longer-duration mission of at least intermediate arm length, provides much greater scientific impact.

Table 4.1: Scientific capabilities for the various sources assuming a 2 year mission lifetime (top panel) and a 5 year mission (bottom panel). For acronyms, see Appendix E; for the notes, see p. 30.

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	2	2	2	2	2	2	2	2	2	2	2	2
total MBHB detected[a]	5–36	7–54	15–165	16–197	8–72	11–98	16–197	16–222	13–133	15–165	16–222	16–266
MBHB sky location[b]	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance [c]	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected [d]	5–90	12–210	21–385	51–830	88–1205	184–2200	38–640	93–1330	176–2090	332–3270	543–4190	760–5010
EMRI position[e]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI luminosity distance[f]	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓
CWD detected/resolved[g]	569	952	1298	2043	3073	4987	5248	8805	9189	14757	13634	21744
CWD position[h]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CWD luminosity distance[i]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
stochastic background[j]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	5	5	5	5	5	5	5	5	5	5	5	5
total MBHB detected[a]	12–90	16–130	21–180	26–244	33–333	83–406	37–441	39–485	39–493	40–548	40–555	40–590
MBHB sky location[b]	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance [c]	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected [d]	12–225	30–525	52–962	127–2075	220–3010	460–5500	95–1600	232–3325	440–5225	830–8175	1360–10475	1900–12525
EMRI position[e]	?	?	?	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI luminosity distance[f]	?	?	?	?	?	✓	?	?	✓	✓	✓	✓
CWD detected/resolved[g]	1001	1680	2283	3607	6056	9905	9200	15550	16150	26050	26900	43200
CWD position[h]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CWD luminosity distance[i]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
stochastic background[j]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 4.2: Scientific returns as a function of configuration, assuming a 2-year mission. For acronyms, see Appendix E; for the notes, see p. 30.

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
The nature of gravity:												
weak field[a]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
strong field[b]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
polarisation[c]	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Fundamental nature of black holes:												
existence of horizon[d]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole mapping (Kerr)[e]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole spectroscopy[f]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Black holes as sources of energy:												
jet formation[g]	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓
transients[h]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
Nonlinear structure formation:												
seed[i]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
hierarchical assembly[j]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
accretion[k]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓
Dynamics of galactic nuclei:												
MBH mass function[l]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI formation channels[m]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
mass segregation[n]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
relativistic dynamics[o]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stellar binary systems:												
formation of compact binaries[p]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
physics of WD mergers[q]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
structure of the Milky Way[r]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
The very early universe:												
1st order EW phase transition[s]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓
other 1st order phase transitions[t]	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓
cosmic strings[u]	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
blue-tilted inflation spectrum[v]	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓	✓	✓
Cosmography:												
Hubble constant[w]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
dark energy equation of state[x]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

Table 4.3: Scientific returns as a function of configuration, assuming a 5-year mission. For acronyms, see Appendix E; for the notes, see p. 30.

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
The nature of gravity:												
weak field[a]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
strong field[b]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
polarisation[c]	?	✓	?	✓	?	✓	?	✓	?	✓	?	✓
Fundamental nature of black holes:												
existence of horizon[d]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole mapping (Kerr)[e]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
black hole spectroscopy[f]	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓
Black holes as sources of energy:												
jet formation[g]	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
transients[h]	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
Nonlinear structure formation:												
seed[i]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
hierarchical assembly[j]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
accretion[k]	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓
Dynamics of galactic nuclei:												
MBH mass function[l]	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI formation channels[m]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
mass segregation[n]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
relativistic dynamics[o]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stellar binary systems:												
formation of compact binaries[p]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
physics of WD mergers[q]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
structure of the Milky Way[r]	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
The very early universe:												
1st order EW phase transition[s]	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓
other 1st order phase transitions[t]	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓
cosmic strings[u]	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
blue-tilted inflation spectrum[v]	✗	✗	✗	✓	✗	✓	✗	✓	✓	✓	✓	✓
Cosmography:												
Hubble constant[w]	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓	✓	✓
dark energy equation of state[x]	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓

Notes to the preceding tables

The following notes are applicable to Table 4.1:

(a) number with S/N > 8
(b) at least 10 MBHBs with $\Delta\Omega < 10$ deg^2
(c) at least 10 MBHBs with $\Delta d_l / d_l < 0.03$
(d) number with S/N > 20
(e) at least 10 EMRIs with $\Delta\Omega < 1$deg ^{2}
(f) at least 10 EMRIs with $\Delta d_l / d_l < 0.01$
(g) number with S/N > 7
(h) $N > 200$ CWD with S/N > 7 and $\Delta\Omega < \pi$ deg^2
(i) $N > 200$ CWD with S/N > 7 and $\Delta\Omega < \pi$ deg^2 and $\mathrm{d}f/\mathrm{d}t < 0.1$, Δlog amplitude < 0.1
(j) S/N >50, and feasibility of the analysis proposed by Adams & Cornish (2010, 2014)

The following notes are applicable to Tables 4.2–4.3:

(a,b) at least one good EMRI detection
(c) N/A
(d) 10 EMRIs with S/N > 20
(e) 10 EMRIs with S/N > 20, and quadrupole moment determination to better than 0.1% ($\Delta Q/Q < 10^{-3}$)
(f) 10 MBHBs with two measurable ringdown modes
(g) 10 MBHBs (S/N > 8) with radio counterpart detectable by SKA, i.e. $\Delta\Omega < 10$ deg^2 and radio flux within 1 μJy
(h) 10 MBHBs (S/N > 8) with radio counterpart detectable by SKA, and with E–ELT (photometry: $m < 31.3$; spectroscopy $m < 27.2$)
(i) 5 MBHBs (S/N > 8) at $z > 7$ (current highest redshift known for a MBH)
(j) 10 MBHBs (S/N > 8) at $z < 7$
(k) 10 MBHBs (S/N > 8) with measurement of both spin directions with respect to the orbital momentum at ISCO within 10 deg
(l) 50 EMRIs with S/N > 20, MBH measurement $\Delta M/M < 0.01$
(m) 20 EMRIs with S/N > 20, eccentricity and MBH spin/EMRI orbit inclination information needed ($\Delta e < 0.01, \Delta\lambda < 1$)
(n) 10 EMRIs with S/N > 20, small BH mass estimate $\Delta\mu/\mu < 0.01$
(o) 10 EMRIs with S/N > 20, eccentricity information needed $\Delta e < 0.01$
(p) $N > 200$ CWD with S/N> 7
(q) $N > 200$ CWD with S/N> 7 and $\Delta\Omega < \pi$ deg^2
(r) $N > 200$ CWD with S/N> 7 and $\Delta\Omega < \pi$ deg^2 and $df/dt < 0.1$, Δlog amplitude < 0.1
(s,t) detection for at least two benchmark scenarios
(u) Nambu Goto strings with small loops, constraining $G\mu$ below 3.3×10^{-9}
(v) detection of waves produced by particle production during inflation
(w) H_0 measured with a 5% accuracy in ΛCDM cosmology (two parameters), merger/ringdown information used
(x) w_0 measured with 30% accuracy and $\Delta w_a < 2$, merger/ringdown information used

The technical assumptions made for the scientific performance yields are as follows:
• 1 Gm arm length: laser power = 0.7 W, telescope diameter = 0.25 m
• 2 Gm arm length: laser power = 2 W, telescope diameter = 0.28 m
• 5 Gm arm length: laser power = 2 W, telescope diameter = 0.40 m

The noise models are as used for the NGO/eLISA study, specifically:
• acceleration noise (original LISA configuration): $3 \times 10^{-15}[1 + (10^{-4}/f)]^{0.5}$ m s^{-2} Hz$^{-1/2}$
• acceleration noise (LISA Pathfinder requirement): $3 \times 10^{-14}[1 + (10^{-4}/f)]^{0.5}$ m s^{-2} Hz$^{-1/2}$
• shot noise = $7.7 \times 10^{-12}\,[0.4/D]^2\,[L/(5 \times 10^9)]\sqrt{(1/P)}$ m Hz$^{-1/2}$
• other measurement noise = 5.15×10^{-12} m Hz$^{-1/2}$

5

Technology developments

5.1 Technology Readiness Level (TRL)

One of the boundary conditions specified for L3 is that the mission must be based on technology that can credibly achieve Technology Readiness Level 6 (TRL 6) by the mission's adoption. As a preamble to the following section, we recall that ESA adopts the following requirements for a specific TRL on the ISO scale:

- TRL1: basic principles observed and reported;
- TRL2: technology concept and/or application formulated;
- TRL3: analytical and experimental critical function and/or proof-of-concept;
- TRL4: component and/or breadboard validation in laboratory environment;
- TRL5: component and/or breadboard validation in relevant environment;
- TRL6: model or prototype in a relevant environment (ground or space);
- TRL7: system prototype demonstration in a space environment;
- TRL8: system 'flight qualified' through test and demonstration (ground or space);
- TRL9: system 'flight proven' through successful mission operations.

5.2 Required technologies

Technology items required for a laser interferometry space mission (both payload and spacecraft elements) have been investigated by the Committee, based on previous technology assessments and roadmaps, as well as on currently on-going developments. In a process similar to that adopted for other ESA L missions, the Committee has prepared a detailed overview of the present status, which compiles:

- the relevant system/sub-system, the associated development area, and the required technology item (for example, within the telescope subsystem, developments are required in the area of pico-metre stability, with the required technology item being the access to materials with sufficiently low CTE, combined with appropriate thermal modeling);
- for each of these items, the top-level technology risks, and a tabulation of any ongoing (funded) activity, along with the relevant funding agency, and the relevant contractor;
- again associated with each technology item, an assessment of the current TRL, the current status and expected development timeline;
- an associated recommended action.

In total, more than 40 such Technology Developments Activities (TDAs) required for L3 have been identified and tabulated (see Appendix C). They have been divided into three groups:

- high priority: critical for the mission, of projected durations up to 3 years, and with priority for an immediate start;
- medium priority: relevant for a payload EM demonstration (see Section 5.4), but in part awaiting other results before embarking on L3-focused developments (the overlap of these developments with that of the EM shown in Figure 7.1 indicates cross-fertilisation);
- low priority: a later start is considered acceptable. These may include technology developments that could reduce cost and/or risk, but which are not on the L3 critical path, and would form part of normal work during Phase B. Other prioritisations may be relevant depending on the EM development requirements.

5.3 Specific technology items identified

Relatively few items have been identified in the first two categories, and they are listed hereafter. For these items, dedicated technology development activities are being initiated in 2016. The High Priority Technology Developments Activities identified are:

1. architecture related: in-field guiding versus an optical assembly tracking mechanism, and the consequences for the backlink, the telescope design and fabrication, and an in-field guiding mechanism;
2. efficient manufacturing of a highly-populated optical bench (e.g., which components demand high stability, and whether assembly can be done robotically);
3. telescope: straylight and manufacturability (including a consideration of on-axis versus off-axis configurations);
4. laser system: primarily the phase fidelity of the power amplifier and power fluctuations at the laser beat frequencies, but including issues of lifetime and redundancy.

The medium priority Technology Developments Activities identified are:

1. gravitational reference sensor, including the charge management system (in part awaiting the LISA Pathfinder results);
2. micropropulsion: choice of cold gas, colloids, or micro-RITs (in part awaiting the LISA Pathfinder results);
3. phase measurement system.

The medium priority items must be monitored during the early system and payload activities, and injected into the planning in time to ensure their readiness for the EM demonstrations, where appropriate. In addition, any further items identified as necessary for enabling the system demonstrators should be injected into the planning.

The identified low-priority items should be picked up in due course, taking into account the system development and need dates. Depending on the architecture finally chosen following the initial Phase A studies, additional technology developments may be required that could not be identified in absence of a more detailed design and analysis.

5.4 Payload Engineering Model phase

The ESA D–SRE Future Missions Office has proposed that a Payload Engineering Model should be developed and validated before mission adoption by the SPC (viz, according to Figure 7.1, before 2025).[1]

There are two main objectives of this approach: to provide early validation of the interfaces between critical component; and to introduce industrialisation of the payload as a means of reducing the development risk for the flight model hardware.

According to the overall schedule presented in Section 7, ESA plans to start the Payload Engineering Model phase (PEM phase) in 2019 Q4, following the completion of Phase A. It will initially be in parallel with a two-year 'technical assistance phase', followed by a two-year Phase B1, which ends with the System Requirements Review. Including a one year margin, adoption of the mission by the SPC would then be targeted in early 2025.

While the following outlines a possible approach, the Committee recommends that, during Phase A, ESA should assemble technical experts in gravitational wave instrument development to set priorities for the overall PEM phase development, tests of subsystem interfaces, and risk reduction testbeds.

Inputs required Amongst the inputs needed before starting such a PEM phase campaign would be:

- a stable mission concept and associated requirements;
- a complete space segment definition, including a detailed design of the payload;
- availability of demonstration models (or better) for critical payload units, including a detailed payload design with specification of the subsystem interfaces;
- a full and detailed definition of the PEM phase, its development plan, and overall objectives. Beyond the unit-level development, issues will likely include:
  - opto-mechanical and thermal integration challenges of the payload;
  - industrial partnering for implementation and integration of payload elements;
  - interplay among optical elements within a single spacecraft, including stray light;
  - challenges in interspacecraft interferometry;
  - metrology system (laser, laser frequency control, and phase measurement).

Detailed objectives Recognising that full performance becomes more difficult to test at an integrated level, the Committee identified several objectives subject to later definition:

- to demonstrate the phase measurement accuracy with one arm;
- use engineering models of critical payload units (laser, telescope, optical bench, charge management, onboard data processing, structure, etc) for pairwise interface testing;
- to demonstrate payload functionality (perhaps split into two or more models);

[1]Concise definitions of the EM, EQM, and QM (adapted from the ECSS guidelines): the EM is flight representative in form and function, without high-reliability parts, used for functional qualification; the EQM combines the EM with flight electronics at MIL standard; the QM is an exact copy of the flight model, but which may be subject to more demanding tests.

- to demonstrate performances in any partially integrated state which support testing;
- to validate critical environmental sensitivities of representative structures (e.g., stability of alignments after vibration);
- to fully demonstrate lifetime issues, e.g. through dedicated tests at unit level;
- as a consequence, determine whether a PEM phase approach implies the use of flight representatives for the laser head, laser operation, telescope, and opto-electronics.

Expected benefits The expected benefits of the proposed PEM phase approach should include:

- a payload industrialisation approach which is anticipated through the PEM phase;
- payload development costs and risks should be mastered;
- a successful PEM phase may lead to a shorter development schedule;
- minimising any development gap following the LISA Pathfinder launch, and thereby federating and preserving the LISA and LISA Pathfinder community and expertise.

As a result of these considerations, the Committee suggests that the 'Payload Engineering Model Phase' includes two components: a series of 'IMS breadboard tests', followed by a set of 'system demonstration activities'.

5.4.1 IMS breadboard test

The interferometry measurement system (IMS) consists of multiple active components which interact with each other via optical and electrical (analog and digital) signals. In the past, several experiments, most notably at JPL and at the University of Florida, have combined commercial or early engineering models to verify the various functions of the IMS at some level.

None of these experiments or early testbeds have combined all payload components, and none have demonstrated the phase fidelity of a full LISA-like IMS. The operation of one or two *Interferometry Measurement System Breadboards*, to test the interaction of all IMS components, would allow the definition and testing of the interfaces between these components early in the development cycle.

It would also foster and facilitate early communication between the various contractors and scientific community experts, and build up critical experience at all levels.

Such activities should start as early as possible, but not later than the start of Phase A, and they should evolve into the following system demonstration activities.

5.4.2 System demonstration activities

A successful demonstration of critical system-level functions is required before mission adoption. These system demonstration activities require a mature mission concept with a fairly detailed payload design, and a well-defined requirement flow down. These system demonstration tasks are scheduled for the years 2020–2024 and form the core of the EM phase. Their general goals are:

- to identify and solve interface problems between all components in a timely manner

- to demonstrate function at some advanced level, and performance where feasible
- to industrialise the payload production process

The system demonstration tasks are expected to combine two or more subsystems to test the functionality and, wherever possible, performance at a more integrated level. This requires mature subsystems which by themselves meet their requirements and provide well-defined interfaces. Performance tests of the entire payload within a single system demonstration will likely be impossible during this phase.

Again, the Committee assumes that Phase A has been concluded by the time the system demonstration tasks start, and that a mature mission design with a well-developed requirement tree exists, with only very few open minor design choices. It is also assumed that all payload subsystems have achieved TRL 5–6, and that models which are representative in form, fit and function to the later flight models are available for the system demonstration tasks.

The Committee has aimed to identify the system risks which should be mitigated or retired during the Payload Engineering Model phase. This list, which assumes that the mission design does not deviate significantly from the old LISA or the eLISA design, focuses on risks associated with interfaces and system aspects, and is not intended to subsume risks associated with the development of individual subsystems. It covers:

1. lock acquisition, proceeding from three misaligned spacecraft to 6 operational laser links;
2. optical system interfaces;
3. phase noise from stray light;
4. phase fidelity of the interferometer readout in a representative system.

In the following we detail each risk and the need for a system demonstration, although the specifics of each risk and of each system demonstration task will depend on the final mission design, which will not be known until after Phase A.

Lock acquisition This has been studied and successfully simulated for the original LISA design, but must be redone as part of the new design study. It has important payload hardware implications (e.g. on the star tracker, photo-diode bandwidth, laser frequency predictability, etc.), as well as for the data acquisition, sensing and control system. Integrated tests should be designed and performed once the signal/constellation acquisition sequence is fully defined.

A lock acquisition test which includes the full dynamics of the expected spacecraft motion is impossible due to the large relative velocities of several m/s between the spacecraft. However, functional tests of a representative payload with ground support equipment representing the two distant spacecraft should be possible. Ideally, this test should go through the entire lock acquisition sequence from misaligned spacecraft to phase-locked laser systems.

Optical system interfaces The optical interfaces between the different subsystems are the most critical interfaces in a LISA-like mission. The laser beam will be injected via an optical fiber launcher onto the optical bench. The optical bench is comprised of many fixed optical components which have to modify, redirect, split and deliver parts of the beam with high accuracy to the optical telescope, the gravitational reference sensor, the backlink fibre, and several detectors on or near the optical bench itself. The optical telescope then sends the beam to the far spacecraft, where it is received by a second, identical, telescope.

Achieving the initial alignment of all components at the required level, and maintaining it throughout launch, cruise phase, and mission operations, is one of the challenges that should be addressed in this system demonstration task. A related issue is the optical quality of the laser beam throughout the interferometer.

The various subsystems will likely be designed and produced by different contractors in different countries. Bringing all these components and contractors together early in the programme should significantly improve communications and interfaces between the contractors and the project.

Phase noise from stray light Light which is scattered out and then back into the laser beams results in phase changes of the laser field inside the interferometer which scales with the amplitude of the scattered light. As long as the back-scattered field has a fixed phase relation with the existing field, the scattered light will not limit the interferometer sensitivity. However, any variations of optical path length will create phase noise, and will limit the sensitivity.

Sources of scattered light include all optical bench components (mirrors, beam splitters, wave plates, lenses, fibre couplers and photo detectors), the telescope mirrors, and the test masses. The most critical components are those which could move by a significant amount ($>\mathrm{nm}\sqrt{\mathrm{Hz}}$) with respect to the optical bench. Worst offenders will likely be the telescopes, test masses, and the fibre couplers. Back-reflection from the photodetectors has also been observed to limit the sensitivity of ground-based detectors.

This system demonstration task is expected to study scattered light, both to anchor scattered light models, and to verify the performance of at least the most critical components.

Phase fidelity of the interferometer measurement system The active components of the interferometry measurement system (IMS) includes the laser systems, the ultra-stable oscillators, the phase modulation systems, the photo receivers, and the phasemeters. The phase fidelity of each of these components, as well as of their various combinations in an IMS-like setup, has already been tested in various testbeds with high fidelity and complexity. However, none of these tests included all active components of the IMS, nor did they include flight-like hardware.

While there is little question that these components can ultimately be combined to form the IMS, there is considerable scope for interface problems, along with miscommunication between project, prime contractor and sub-contractors, which potentially delays the mission and/or increases cost. This system demonstration task should identify and solve interface problems early in the project, as well as helping to industrialise the production and testing of the IMS. It should evolve from phase fidelity tests in earlier breadboard level models.

5.4.3 Conclusions

An early PEM phase, viz. before SPC adoption, would be unusual in the development cycle of a space mission, but is motivated by certain specific and worthwhile objectives. Accordingly, the Committee endorses significant early investments in the development of gravitational wave detector engineering models, risk reduction activities, and testbeds as being in the best interest of a successful mission.

Adding a development cycle involving early fabrication of an end-to-end payload of even modest fidelity would follow a pattern often used in industrial developments.

It must be stressed that the expected financial effort would be substantial, and broadly commensurate with the full payload non-recurring costs. A successful PEM phase would therefore also require funding, suitable organisation (including appropriate levels of system engineering and management), respective contributions from ESA and partners for the payload, and would presumably require a proto-consortium to be in place.

5.5 Lessons Learnt during LISA Pathfinder development

In addition to the accumulated knowledge and experience of ESA and the Committee members in assessing the L3 schedule, specific consideration has been given to the 'lessons learnt' during the development of LISA Pathfinder. Though an official ESA 'lessons learnt' document is not yet available, the following specific and critical issues were brought to the attention of the committee:

- a lack of space heritage led to a substantial overestimate of the technology readiness;
- the basic concepts turned out to be robust, but the transition to TRL6 was slow;
- the partners initially agreed to go directly to a proto-flight model (PFM), while in the end equipment qualification models (EQMs) had to be implemented for almost all critical items during the development phase;
- the need for strong, top-down, system engineering from Phase 0 through to Phase E was underestimated;
- some tasks originally considered as standard engineering were underestimated, and constituted the main sources of delays, in particular redesigns driven by:
  - the launch lock motor;
  - a poorly qualified brazing procedure for the inertial sensor assembly;
  - the electric μN-thrusters (FEEPs).

In terms of heritage, it should also be stressed that numerous drag-free spacecraft followed the TRIAD demonstration navigational satellite in 1972, with LISA Pathfinder's proof-mass system conceptually derived from the ONERA accelerometers which have flown on Champ, GOCE, GRACE, and others.

6

Data analysis

6.1 Overview of the principles

There are considered to be no conceptual barriers to the principles of the laser-interferometer data analysis. The total satellite data volume is small – operating in the $10^{-4} - 10^{-1}$ Hz band, a sampling rate of order 1 Hz yields a total scientific volume of $\sim 2x10^8$ points per year, assuming 6 links. At the same time, there are substantial computational (and associated organisational) challenges for the numerical processing.

Regarding the proof masses as responding to the superimposed ripples in spacetime as a result of many thousands of gravitational wave sources of unknown form, frequency, and sky location, the data is expected to be signal dominated, and the numerous gravitational wave signals overlap in time and in frequency. The high signal-to-noise ratio of the majority of the signals is expected to guarantee their confident detection. The main data analysis task is then to disentangle them, and accurately determine the source parameters. Data analysis pipelines will aim at a global fit, implementing a procedure which is iterative both in time and in the number of source signals. The potential presence of instrumental artifacts adds significant complexity to the data analysis.

Addressing the organisation and operational aspects of the required ground processing, CNES has recently completed a Phase 0 study of such a ground segment.

6.2 Matched filtering

Matched filtering is presently considered to be the most effective way of estimating and disentangling the gravitational wave signals. This implies that the phase of the gravitational wave must be tracked with an accuracy of better than 1 rad in total over the entire duration of the signal 'in band'. Matched filtering proceeds through a (very large) set of templates (signal models with different parameters) and finding the one that best matches the observed data, by finding the maximum of the likelihood function. This imposes a very stringent requirement on the accuracy for the gravitational wave signal models.

The most successful data analysis methods are stochastic (as compared to the grid-based search adopted for LIGO–Virgo), and these include parallel tempering Markov Chain Monte Carlo, nested sampling, and multimodal genetic algorithms. The problem is complicated by the multi-modality of the likelihood surface, and the many parameters per source.

Although the strongest gravitational wave from EMRIs may easily be distinguished from the

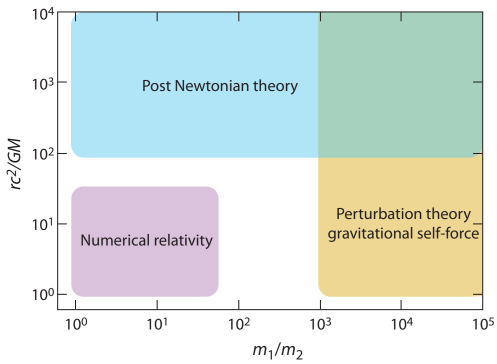

Figure 6.1: The different computational methods that are currently used to model compact object binary systems, and generate their expected waveforms, as a function of $GM/rc^2 \sim v^2/c^2$ and m_2/m_1.

instrumental noise of the gravitational wave detector, most signals will be deeply buried in instrumental noise. However, since an EMRI will go through many gravitational wave cycles before making the plunge into the central supermassive black hole, it should still be possible to extract the signal using matched filtering. In this process, the observed signal is compared with a template of the expected signal, amplifying components that are similar to the theoretical template. This requires accurate theoretical predictions for the wave forms, including accurate modelling of the EMRI trajectory.

6.3 Different computational methods

The equations of motion in general relativity are notoriously hard to solve analytically and, in general, some sort of approximation scheme is required. Two source parameters determine the range of validity of the various computational methods currently available to model compact object binary systems (Buonanno & Sathyaprakash, 2014): $GM/rc^2 \sim v^2/c^2$ and m_2/m_1, and the relevant domains are shown schematically in Figure 6.1.

In the case of extreme mass ratio inspirals, for example, the mass of the compact object is much smaller than that of the central supermassive black hole, allowing it to be treated perturbatively, for example through post-Newtonian expansion, or through numerical relativity (by solving the equations of motion numerically). The non-linear nature of the theory makes this very challenging, but significant success has been achieved in numerically modelling the final phase of the inspiral of binaries of comparable mass. The large number of cycles of an EMRI make the purely numerical approach prohibitively expensive in terms of computing time.

6.4 The Mock LISA Data Challenge

Aside from the challenge of computing waveforms for the vast range of systems likely to be encountered, the 'Mock LISA Data Challenge' task force was formulated in 2005 to demonstrate, by simulation, that the scientific requirements of a LISA-like mission could be met, while developing a common framework for comparison of various data analysis methods. The resulting challenges, of increasing complexity, and totaling some 70 participants from 25 institutes, were produced roughly once a year since then: MLDC1 in 2006, MLDC2 in 2007, MLDC3 in 2008–09, and the data challenge for MLDC4 released in 2009 (Figure 6.2).

	MLDC1	MLDC2	MLDC1B	MLDC3	MLDC4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	• Galaxy: 3 x 10^6	• Verification • Unknown isolated • Unknown interfering	• Galaxy: 6 x 10^7 (chirping)	• Galaxy: 6 x 10^7 (chirping)
Massive black hole binaries	• Isolated	• 4-6 over Galaxy and EMRIs	• Isolated	• 4-6x spinning/ precessing over Galaxy	• 4-6x spinning/ precessing, low mass
EMRIs		• Isolated • 4-6 over Galaxy and MBHs	• Isolated	• 5 together (weaker)	• 3x Poisson (2)
Bursts				• Cosmic string cusp	• Poisson (2) cosmic string cusp
Stochastic background				• Isotropic	• Isotropic

Figure 6.2: Summary of the data sets included within the various Mock LISA Data Challenges. The data release and corresponding analysis for MLDC1–3 was carried out during 2006–2009. The data released for MLDC4 in 2009 have never been fully analysed.

From these rounds of the mock data challenge, it is considered known (i) how to detect and subtract resolvable white dwarf binaries; (ii) assuming that resolvable white dwarf binaries are subtracted, it is known how to detect (of order) five supermassive black hole binaries with signal-to-noise between 12–1500 on top of the white dwarf stochastic foreground; (iii) how to detect individual EMRIs with signal-to-noise down to ~ 20 in isolated Gaussian data sets. However, as a consequence of the announcement of the L3 launch date in 2034, priorities and national funding for the associated data analysis efforts have been downgraded, and the data released for MLDC4 in 2009 have never been fully analysed.

6.5 Immediate challenges

Improving the waveforms (e.g. by incorporating more physics into the MBHB waveforms, such as spin, higher harmonics, inspiral, merger and eccentricity) promises to enhance the science performance significantly, by improving astrophysical parameter estimation and by breaking degeneracies. There are also practical improvements like improved representation of the detector response function and the speed of Bayesian integrations.

In the context of the present evaluation, the LISA/eLISA teams have identified two rather critical milestones/tasks, which were only partially addressed previously, and which play a key role in the further data analysis development. The first picks up where the previous MLDC left off, viz. disentangling multiple gravitational wave signals (either of the same or of different type) with the simplifying assumption of Gaussian instrumental noise. The second task addresses the question of the presence of instrumental artifacts and their effect on the performance of the data analysis algorithms. Both tasks are considered as somewhat time critical, since the outcome of the study may have a non-negligible impact on the mission design.

6.6 Longer term challenges: EMRI waveforms

As mentioned above, detecting EMRIs and measuring their parameters accurately is challenging because the waveform is buried below the noise and of long duration. In order to apply optimal matched filtering it will be necessary to match the real waveform with a model waveform that is accurate to better than one radian of phase over 10^5 cycles.

The Mock LISA Data Challenge has shown that it is possible to detect these waveforms and match them against Gaussian noise and against the frequency modulation imposed by the orbit of the spacecraft. But this has been done using ‘toy’ waveform models that incorporate the complexity of the real EMRI waveform family but do not adequately match any of the real waveforms. The reason for this is the difficulty of adequately approximating realistic EMRI orbits in general relativity. By extending the Mock LISA Data Challenge, it can be confidently expected that it will be shown to be possible to extract EMRI signals from data with realistic instrumental noise and with the confusion background of white dwarf binaries and other EMRI signals.

For L3, accurate inspiral orbit solutions over 10^5 cycles must be available in order for the data analysis templates to match the real signals. If the problem can only be solved for a smaller number of cycles, then it will be necessary to ‘patch’ solutions together with extra parameters representing phase jumps, and that will reduce the sensitivity of searches. The family of distinguishable EMRI waveforms is very large, so a full solution will require two components that are not yet in place and that will require significant theoretical work in general relativity.

The EMRI problem is particularly challenging as a problem in theoretical physics. The large mass ratio makes it necessary to use perturbation theory of general relativity, describing the small infalling black hole as a perturbation on the fully relativistic Kerr black hole background generated by the massive black hole. The radiation emitted by an orbiting body must be computed and then used to calculate the back-reaction on the body that leads to its inspiral. Solving the wave equation on the Kerr background is an understood problem, but a rather complex one because the solutions involve non-standard functions that need to be computed. There is therefore a large computational demand even to compute a single self-consistent inspiral waveform. The first requirement for EMRI searches is therefore the development of efficient computational algorithms that can compute individual waveforms of sufficient length for arbitrary parameter values. Programs already exist that can successfully compute long waveforms for certain parameters (non-spinning black holes, for example). What is needed is to extend this development to longer waveforms and larger ranges of parameter values.

The second component is to incorporate computed waveforms into search algorithms that have to scan large parameter spaces for a match to a signal in the data. It is unrealistic to expect to compute an accurate waveform ahead of time for each set of parameters. LIGO searches address a similar problem for black hole merger waveforms that have to be computed using nonlinear general relativity simulations. They do this by creating an analytic waveform (Effective One Body, EOB) that is tuned to parameter sets where full computations are available and that then can be shown to be accurate enough for other parameter sets. This is a possible approach for EMRIs, although the analytic family needs to match 10^5 cycles instead of 10–20 cycles as in the case of LIGO. This should be pursued to estimate at least whether it is feasible for EMRIs.

Another approach would be to devise very fast computer codes that can compute EMRI waveforms accurately on the fly, and then devise search algorithms that use these to iterate on candidate waveforms. Perhaps the full solution will need both of these approaches.

There is no reason to expect insuperable difficulties in creating these two final components in the time available before launch. However, the long time to L3 has led some funding bodies in European countries to reduce LISA research support across the board, including for these items. We recommend that ESA attempt to stimulate support for the European theory groups that are capable of doing this development. It is prudent to start soon because the problem will need both intensive theory work and development of new and efficient computing methods.

7

Schedule

The Committee has worked with the D–SRE Future Missions Office to construct a development schedule for L3 consistent with the target 2034 launch date (Figure 7.1). SPC/IPC decisions have been assigned their 'normal' schedules, while the full ITT process of technology developments (including approval) is assumed to require 9 months. This takes into account the following principles (item numbers correspond to those in the figure):

- (2) no substantive activities start in advance of the first LISA Pathfinder in-orbit results (assumed mid-2016);
- (3) a 'Call for Mission Proposals' is issued in late 2016. The community response must identify a mission satisfying the SSC requirements, as well as potential scientific and payload partners;
- (4–7) early development of the most critical Technology Development Activities (TDAs), as summarised in Section 5, should get underway before the end of 2016;
- (4–8) high- and medium-priority TDAs are concluded before start of the EM definition;
- (10–15) demonstration of the payload concept is completed before mission adoption, through a Payload Engineering Model phase with a projected development duration of 4 years. TRL 5–6 is to be achieved before project adoption/approval;
- (17–18) a Phase A study comprising parallel (competitive) industrial studies is undertaken with the support of the payload consortia, ensuring interface definitions and closure of major trade-offs. Industrial competition is maintained until mission adoption;
- (19) a parallel 'technical assistance phase' provides industrial continuity between Phase A and Phase B1;
- (22) while a 1-year schedule margin around 2024 is present in this plan, its availability evidently depends on the successful and timely conclusion of the TDAs and PEM phase;
- (25) the spacecraft schedule assumes 8.5 years for Phases B2/C/D, including margin.

We stress that this is a schedule prepared to match the mandated 2034 launch date, with activities making maximum use of this 18 year period to retire risk and demonstrate timely achievement of the specified TRLs.

The Committee was not asked to evaluate an 'expedited' schedule determined only by technology development, and not by financial or other programmatic constraints.

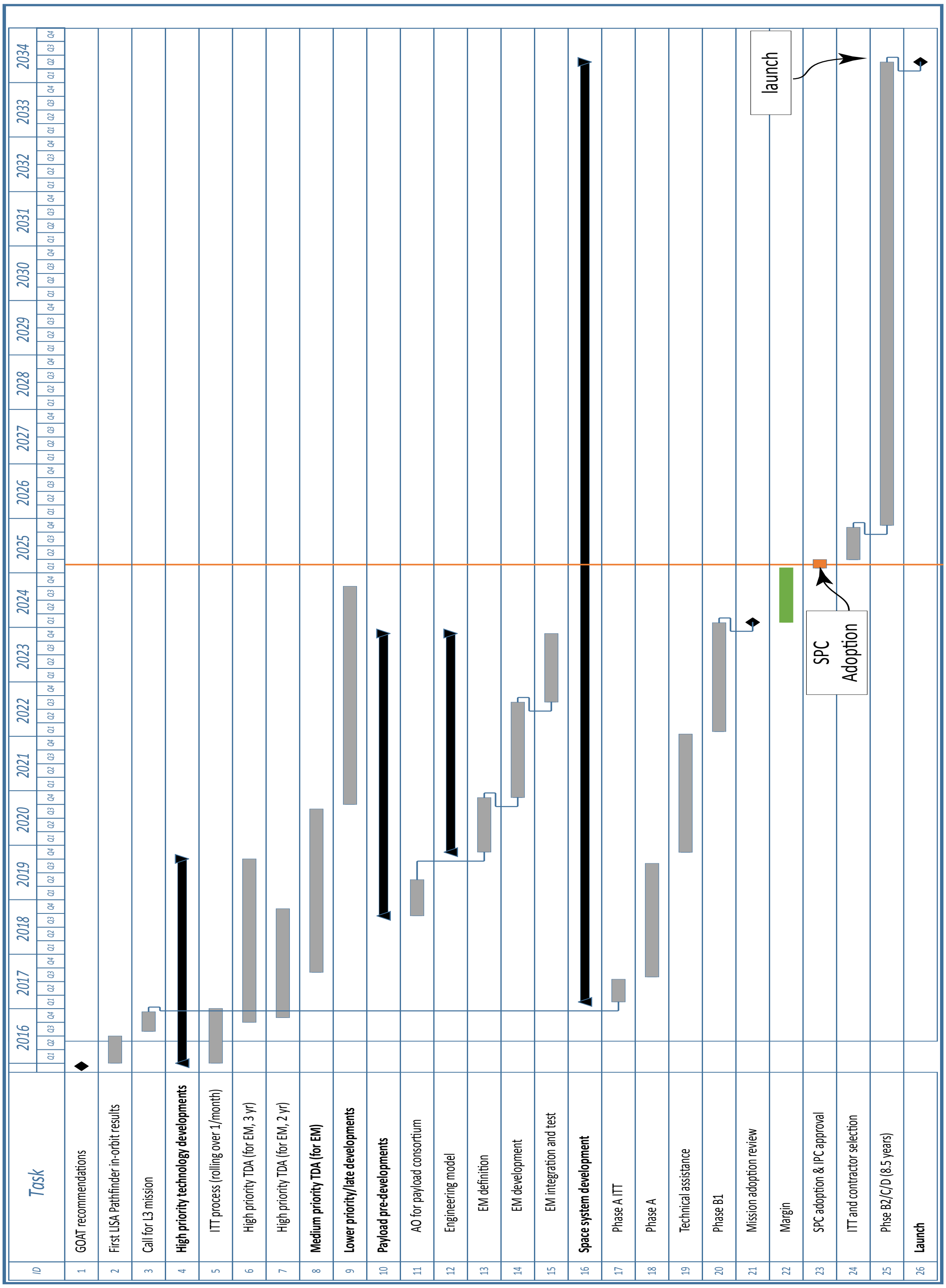

Figure 7.1: Preliminary schedule, showing the technology development timeline, formal decision points, and project phases, consistent with the targeted 2034 launch date. The schedule has been prepared by the D–SRE Future Missions Office (F. Safa and M. Gehler) with inputs from the Committee. Note that this is for preliminary planning purposes, and is not to be construed as an 'approved' schedule.

8

Costs

8.1 Boundary conditions

According to this Committee's mandate, the L3 mission will be European-led, with a cost to ESA not to exceed 1 B€ (2014 economic conditions), plus an expected national contribution of order 25% of the ESA cost. International participation is expected to be limited to elements not exceeding approximately 20% of the total mission cost.

At the start of the Committee's work, it was explicitly stated by the Executive that the Committee was not expected to attempt a revised quantitative estimate of the L3 mission cost. Such a task is notoriously complex for all space missions and, in the case of L3, further complicated by some of the factors which are beyond the Committee's authority, and which will have a strong influence on the final mission cost. Examples are:

- the selected mission configuration, which will be largely dependent on the choice of arm-length, number of links, and mission duration. No attempt has been made to estimate whether any specific configuration would fit into the proposed budget envelope;
- the hardware split between the presently-unknown international partners;
- ESA's role and scope in the payload (for example, whether it will be responsible for the payload management, system engineering, and AIV, or whether it will also pay for items such as the lasers, telescopes and microthrusters);
- the structure, scope, and funding of the Payload Engineering Model (PEM) phase.

8.2 Specifics of L3

For completeness, we list some of the specifics of the L3 mission that will need to be taken into account in any future rigorous costing exercise. The ESA project Cost at Completion normally includes studies, project oversight (management), the space platform (spacecraft), AIV, launcher and launch operations, operations, and data collection. In the case of L3 there are a number of specific factors which must be taken into account:

- the (substantial) costs of the LISA Pathfinder technology demonstrator are not included in the L3 costing, but the motivation was to retire many of the risks associated with technologies which could not convincingly be demonstrated on-ground. The LISA Pathfinder project has led to the delivery, in fully space qualified form, of many of the main payload subsystems needed for L3. Accordingly, LISA Pathfinder will have reduced the level of project contingency funds required for a number of significant elements of L3;

- working in the sense of risk reduction, it should be stressed that the basic concept of a 3-spacecraft laser interferometry system has been largely unchanged since LAGOS in 1985, thirty years ago. The concept has been the subject of extensive study, including the period between 2005–2011 (Section 1.2) almost corresponding to a 6-year Phase A study;
- the mission will require three space platforms which, in the 6-link configuration, will be of identical design. There should be reductions in platform costs compared to those for three completely different satellite designs, but the reductions are not straightforward to quantify, for example being dependent on manufacturing approach and build sequencing. In a similar way the payload elements will require multiple instances. Cost reductions from quantity production may be available (recurrent versus non-recurrent costs), but there will be further costs arising from the need to manufacture multiple subsystem models, especially if these are carried out sequentially rather than in parallel;
- the mission is not yet fully defined. There has been no final decision on the number or length of the interferometer arms, laser power, telescope entrance diameter or mission lifetime, all of which have an influence on the mission cost, either through platform design or launcher requirements;
- considerable cost differences can result from the selected model philosophy, which will therefore require careful consideration on requirements especially given LISA Pathfinder and the currently-baselined payload Engineering Model;
- if a major contribution to L3 from NASA is assumed (there is no agreement between the Agencies yet on the division of mission responsibilities), the difference in ESA/NASA costing methodologies complicates total cost estimates, and therefore also a fractional share. For example, NASA characteristically pays for all payload elements under its responsibility, and full staff costs. ESA typically does not pay for the full payload, while different European countries have different approaches to costing work at institutes (e.g., for permanent staff);
- recent trends in decreasing launch costs also have a significant impact on mission costs.

8.3 Reported costs for LISA and eLISA

ESA's latest costing for a laser interferometry mission was conducted in the context of the L1 selection, and in the LISA to eLISA de-scoping exercise. Indicative costs were around 1.0–1.2 B€. NASA has carried out several (extensive) cost estimates of a variety of different LISA-like mission scenarios which, for the reasons outlined above, are usually (substantially) higher than the European estimates (using a generic dollar to Euro conversion rate).

Nevertheless, both ESA and NASA exercises suggest that the mission costs are a relatively weak function of the mission configuration. While mission costs differing by some 100 M€ are of considerable significance, it should also be stressed that, for a given costing model, savings of much more than 10% in going from LISA (6 links, 5 Mkm armlength, 5-year mission) to eLISA (4 links, 1 Mkm armlength, 2-year mission) seem non-trivial to achieve in practice. Stated equivalently, mission complexity and cost change rather weakly with science capability for a given concept, even for rather drastic reductions in science capability. Conclusions of published NASA costings have also suggested that, broadly, giving up more than half the science saves about 10% in cost (Stebbins, 2009).

9

Payload contributions

The economic boundary conditions for L3 stipulated by ESA, state that L3 will be European-led, with a cost to ESA not to exceed 1 B€ (2014 economic conditions), plus an expected national contribution of order 25% of the ESA cost. Furthermore, international participation will be limited to elements not exceeding approximately 20% of the total mission cost.

9.1 European contributions

This process has been started from the European side. In early 2016, ESA convened the *'Gravitational Wave Observatory Working Groups'*, with nationally appointed scientific representatives, whose Terms of Reference have been agreed with delegations. The Working Groups started their activities, under the coordination of the Future Missions Office, in 2016 March, and with a projected duration of about 1 year. The objective is to define a possible partitioning of hardware contributions, that will only be formally confirmed, by delegations, at the end of the process. Major commitments on funding are only expected at the time of the mission adoption, nominally in early 2025.

In parallel, NASA will be running a US-centred exercise with similar objectives, the goal being to merge the outcomes of these two processes around the end of 2016. The intention is then to proceed with coordinated activities in 2017, having ensured that all elements are covered, and that possible duplications are known and appropriately coordinated.

9.2 NASA contributions

9.2.1 NASA plans for a future gravitational wave mission

NASA's current plan for conducting gravitational wave astronomy from space is to seek a minority role in ESA's L3 mission. A joint NASA/ESA gravitational wave mission was the third recommendation in the large category of the 2010 decadal survey (see *New Worlds, New Horizons*, Committee for a Decadal Survey of Astronomy and Astrophysics 2016). The decadal survey process establishes the target science for NASA's Astrophysics Division. The Astrophysics Implementation Plan, the Division's response to the decadal recommendations, states NASA's intention to seek a partnership with ESA in L3, the third large class mission in ESA's Cosmic Visions 2015–2025 Programme.

NASA has expressed its interest in L3 participation through informal discussions with ESA Headquarters. ESA has responded by inviting NASA to name three members, and one agency observer, to this Gravitational Observatory Advisory Team. In parallel, ESA also invited Dr. Paul Hertz, the Director of the Astrophysics Division, to propose flight hardware that NASA might supply. An initial list has been provided.

As part of the decadal survey process, NASA asks the National Research Council (NRC), the operating arm of the National Academy of Sciences that produces the decadal surveys, to review the Astrophysics Division progress against the decadal recommendations at the middle of the decade. That review is in progress as of this writing.

The Astronomy and Astrophysics Midterm Assessment commenced on 2015 October 8. The committee has met several times and a final report is in preparation. The final report is expected to be released on or shortly after 2016 May 1. NRC recommendations are generally kept confidential until the report is released, and then they are made publicly available (details of committee membership, meeting schedule, agendas, presentations, etc. are given at `sites.nationalacademies.org/SSB/CurrentProjects/SSB_161177`).

The Astrophysics Division has already started preparations for the 2020 decadal survey. The Division plan for those preparations is laid out in a white paper that is publicly available. NASA participation in L3 will require a strong recommendation from the 2020 decadal. The Astrophysics Division has initiated the L3 Study to assess the roles that NASA might play in L3, and to advise Dr. Hertz about the science, risk and cost consequences. The L3 Study Team (L3ST) will also prepare materials to submit to the 2020 decadal survey process when it commences circa 2019 (details of the committee membership, meeting schedule, agendas, documents, etc. are given at `http://pcos.gsfc.nasa.gov/studies/L3/`). NASA invited ESA to name an observer to participate in the NASA L3 Study. The L3 Study Team held its kick-off teleconference on 2016 February 17.

9.2.2 NASA activities leading to a gravitational wave mission

NASA supports two broad areas of technical work preparing for a future gravitational wave mission, namely participation in ESA's LISA Pathfinder mission and development of technologies for a space-based gravitational wave observatory.

ESA's LISA Pathfinder mission has been a joint ESA/NASA undertaking since its inception in 2000. The original mission goal was a demonstration of disturbance reduction through 'drag-free' flight and the validation of a disturbance error budget. The success of LISA Pathfinder has been a critical requirement in both ESA's selection process and NASA's decadal surveys.

NASA contributed its ST7 Disturbance Reduction System to LISA Pathfinder. The ST7 project was originally a part of NASA's New Millennium Program for technology demonstrations. However, the ST7 project encountered budget and schedule challenges and was substantially de-scoped in 2004. The final flight hardware only included the colloidal micronewton thrusters and drag-free controller; NASA test masses and metrology interferometer were de-scoped out of the package. NASA's drag-free controller is intended to operate the colloidal micronewton thrusters using the ESA test masses and sensing system.

The colloidal micronewton thrusters were successfully commissioned in-flight during January 2016 while the Pathfinder spacecraft was en route to L1, the first Sun-Earth Lagrange point. The ST7 operations period begins after the ESA operations period completes, expected to be in mid to late June 2016.

ESA has invited NASA to participate in the analysis of data from the LISA Technology Package, the European payload on Pathfinder. US researchers will be collaborating with the

Pathfinder science team during the ESA science operations, expected to start in early March. The US researchers have been collaborating on test planning and operations simulations for a couple of years.

In the area of interspacecraft interferometry the US and Germany have invested considerably in a first demonstration of interspacecraft interferometry with the Laser Ranging Interferometer on the GRACE Follow-On Mission. Flight hardware has been delivered to the spacecraft, with launch scheduled in late 2017. Funding and motivation for this activity come from the Earth Science area, but with large technical and programmatic overlap with LISA as described in Section 1.4.

For several years NASA has been developing a number of technologies needed for a space-based gravitational wave detector based on laser interferometry. The following technologies received funding in recent years:

- telescope subsystem
- phase measurement subsystem
- laser subsystem
- micronewton thrusters
- arm-locking demonstration for laser stabilisation
- gravitational reference sensor
- multi-axis heterodyne interferometry (test mass/interferometer interface)
- ultraviolet LEDs for test mass charge control
- optical bench designs to facilitate manufacturing
- inter-spacecraft interferometry demonstration on GRACE Follow-On

There is also a low level of support for developing science and data analysis techniques. In the past, this research has been pursued by collaborations of US and European researchers. This will increase again with science performance analyses in the L3ST.

9.3 JAXA/ISAS contributions

JAXA/ISAS defines their three budget categories as medium-class missions, small-class missions, and international collaborations. The latter, estimated at about $10 Million per year in total, are open for community application. Although the Japanese Gravitational Wave community is looking for a possibility to contribute to the ESA L3 mission, no decision has been made at this time.

10
Conclusions

The Committee's Terms of Reference were paraphrased in the Executive Summary as follows:

(a) is the mission technically feasible?
(b) is laser interferometry still the best approach for a gravitational wave space mission?
(c) how can the technical development of L3 be organised to minimize cost and schedule?

The Committee has identified no fundamental technical issues which might question or invalidate the measurement of gravitational waves from a laser interferometry based space mission.

Based on an evaluation of the alternative measurement approaches, laser interferometry remains the preferred option. Only atom interferometry appears to offer a plausible alternative, and its current readiness would almost certainty make it a more risky alternative if baselined today.

An outline for the prioritised technology development has been presented, which very comfortably matches the launch schedule specified in the Committee's brief.

Technological feasibility does not, of course, ensure that mission success within the cost and financial envelope specified can be guaranteed. We underline that no new or independent costing analysis has been attempted as part of this activity, for the reasons noted in Section 8.

As importantly, the success of any complex space mission depends crucially on the industrial organisation, overall project management, and the scientific advisory teams.

The February 2016 announcement of the detection of the first gravitational waves with Advanced LIGO, opens the way to a new, feasible, powerful, and revolutionary window on the observable Universe, also raising the question of whether the profound importance of these developments should lead to a reassessment of the current schedule for L3.

The launch and successful commissioning of LISA Pathfinder is a major milestone for the L3 mission. The technical and scientific knowledge base now residing in Europe argues for the early implementation of a gravitational wave observatory under European leadership.

For other key conclusions, we refer to the Executive Summary.

A. Acknowledgements

The Committee is grateful to various individuals who have generously supported its activities.

The ESA staff listed on p. ii attended most of the meetings, and assisted in numerous ways. Martin Gehler, Oliver Jennrich, and Frédéric Safa provided a number of specific contributions reflected in this report.

The LISA Pathfinder Project Manager (Cesar Garcia Marirrodriga) and Project Scientist (Paul McNamara) gave insightful presentations on the LISA Pathfinder mission, giving their time at a very pressing period in the launch preparations.

From the eLISA scientific communities, many scientists have assisted in running the extensive numerical simulations which have provided the substance of Chapters 2–4. In particular we are grateful to Dr Stanislav Babak (Albert Einstein Institute, Golm), Dr Alberto Sesana (University of Birmingham), and the other members of the eLISA scientific working groups: E. Barausse (IAP, Paris), E. Berti (University of Mississipi), C. Caprini (IPht, Saclay), R.H. Cole (University of Cambridge), J.R. Gair (University of Cambridge), A. Klein (University of Mississipi), C.J. Moore (University of Cambridge), G. Nelemans (Radboud University, Nijmegen), A. Petiteau (APC, Paris), and E. Porter (APC, Paris).

B. Other detection technologies

The current designs for gravitational wave detectors use interferometry of laser beams between mirrors as macroscopic test masses or, as proposed more recently, interferometry of atomic wavefunctions using clouds of atoms as test masses. Since the 1960s, the goal of gravitational wave detection has inspired a variety of other ideas, many of them only ever appearing as single theoretical papers outlining the concept and never coming to the point of experimental development. However, prior to the commencement of the L3 hardware phase it is necessary to select the baseline technology for the mission so allowing the start of technological developments and industrial contracts which lead coherently towards the flight hardware delivery.

As a step towards the selection of the baseline technology, the Committee has reviewed all the known technologies proposed for gravitational wave detection in the literature.

Technology Readiness Level An important issue in such an assessment is the state of technical readiness of a proposed detection scheme. The system of Technology Readiness Levels (TRL, Section 5.1) is useful to separate those proposals which exist only at the early conceptual level from those for which some laboratory tests have been carried out in a representative environment, acknowledging that the environment in this case reflects the condition during launch and in orbit.

Since several of the proposed technologies have not reached the stage of having their basic principle observed and reported, the additional level of TRL0 is adopted for this survey, defined as having no analysis of the most likely noise sources or system architecture.

Critical in credible publications of proposed detection technologies is some assessment of both the internal detector noise (either quantum or thermal in nature) and the external or environmental noise which often sets the detection limit. Many of the papers outlining alternative detection schemes do not include estimates of this external noise and therefore their claimed sensitivity must be considered questionable with the resulting level of TRL0.

ESA requires the critical technologies in a mission proposal to be at TRL6 at the time of project adoption, and therefore a current TRL level below 5 would present serious schedule and development risks for an L class mission in the ESA programme.

Frequency range Many of these alternative concepts work at frequencies at which no strong astronomical sources are currently anticipated. However, the possibility of a gravitational Hertz experiment is a logical motivation and in principle this could be carried out at any frequency.

Gravitational Hertz experiments therefore justify the development of detectors at frequencies at which no known astronomical sources will radiate.

In the context of the Senior Survey Committee (SSC) report, which set the science goals for the L3 mission, by far the most fruitful frequency range for a space mission is the 0.1–100 mHz band where known strong astronomical sources of gravitational radiation exist and current models indicate that these sources will be detectable with the sensitivity likely to be available within the format of an ESA L Class mission. In simple terms this sensitivity requirement is a detectable strain of $3 \cdot 10^{-20} / \sqrt{\text{Hz}}$ at frequencies between 1–10 mHz.

The accompanying table lists the technologies reviewed during this study as a means of ensuring that no viable technology which could achieve the required sensitivity was omitted from the initial technology assessment. No attempt was made to analyse the very wide range of architectural options proposed using laser interferometry as the basis. These include the choice of arm numbers, the use of time delay interferometry, squeezed states, spherical test masses, etc. These choices are left to the instrument proposers and science team.

Several technologies have been proposed in which the basic interaction, usually with an electromagnetic field, is frequency independent and therefore could be used in the L3 frequency band. However none of these proposals assess sensitivity and external noise sources at the relevant frequencies and none of them have advanced beyond the publication of the physical concept. They have therefore been assigned TRL0.

Possible technologies Four possible technologies have been optimised to the L3 frequency band: laser interferometry, cold atom interferometry, the oscillation of Cosserat rods, and the torsion bar. The latter covers some of the L3 frequency band and experimental data is being generated in laboratory tests of such a system. However, as reported by the proposers the sensitivity is very unlikely to be better than 10^{-17} and this disqualifies the concept from the present consideration. The proposed use of the induced oscillation of Cosserrat Rods has not been advanced beyond the initial concept and no estimates of environmental noise have been published nor is there any credible system architecture, leaving this proposal at TRL0.

The technical status of matter wave interferometry is changing rapidly. Cold atom technology promises some simplification of the payload because test mass charging may not be a problem, In addition, there is the possibility that an end-to-end system test may be possible on ground, a procedure not practical with macroscopic test masses. However the technology has not yet been demonstrated in the laboratory at the required level of sensitivity. Despite recent advances in the proposed system architecture, the technology must be rated no higher than TRL3. No serious industrial study is yet available to demonstrate how a cold atom interferometer could be incorporated in a space mission. A combination of lab demonstrations and industrial studies is now needed in order to progress a cold atom payload to the point at which it could be considered a backup for laser interferometry.

Conclusions The outcome of the technology review is therefore straightforward. Of all the technologies assessed only laser interferometry offers the necessary sensitivity in the frequency range identified, and at a level of technical maturity appropriate for the adoption of an L class mission in the ESA programme. This conclusion is independent of the current success of laser interferometry in ground based gravitational wave detectors such as Advanced LIGO and Virgo, and also independent of the choice of technology for LISA Pathfinder.

As far as the current state of the art is concerned this is the only technology that meets all the requirements. It should be noted, though, that such a choice is indeed reinforced by the fact that ground based detectors routinely achieve a displacement sensitivity a factor of 10^8 better than LISA requires and that much of the technology will have been tested on LISA Pathfinder. Both these factors suggest that the choice of laser interferometry as the baseline technology for L3 carries with it a relatively low programme risk.

Table 1: Alternative technologies for gravitational wave detection from space

Technical concept	Frequency of operation	Sensitivity	Reference	Disqualification
Resonant bar	600Hz–1 kHz	$4 \cdot 10^{-21}$	Astone	frequency
Laser interferometer on ground	10 Hz–10 kHz	10^{-22}	Gershenstein	frequency
Laser interferometer in space	0.1–100 mHz	$3 \cdot 10^{-20} / \sqrt{\text{Hz}}$	Faller & Bender	[none]
Displacement noise-free laser interferometer in space	100 Hz	$2 \cdot 10^{-23} / \sqrt{\text{Hz}}$	Wang	frequency
Atom interferometer on ground	1–10 Hz	10^{-19}	Dimopoulos	frequency
Atom interferometer in space	0.1–100 mHZ	$5 \cdot 10^{-20} / \sqrt{\text{Hz}}$	Dimopoulos	low TRL (2?)
Mechanical deformation of high Q microwave cavity	1 MHz	10^{-17}	Reece	frequency
Conversion of GW to EM waves in static magnetic field	frequency independent	10^{-21}	Gershenstein	TRL0
Conversion of GW to EM waves in static electric field	frequency independent	no prediction	Lupanov	TRL0
GW effect on EM wave direction	frequency independent	no prediction	Fakir, Labeyrie & Bracco	TRL0
GW effect on EM wave frequency	frequency independent	no prediction	Baierlein	TRL0
GW effect on EM wave amplitude	frequency independent	no prediction	Zipoy	TRL0
GW effect on EM wave polarisation	frequency independent	no prediction	Cruise	TRL0
Resonant polarisation rotation	100 MHz	10^{-17}	Cruise	frequency
Seismic stimulation of the Earth	0.05–1 Hz	10^{-13}	Coughlin & Harms	sensitivity
Seismic stimulation of the Earth	60.1 Hz	10^{-17}	Levine & Stebbins	frequency
Seismic stimulation of the Sun	20–100 μHz	$6 \cdot 10^{-9}$	Seigel & Roth	frequency
Suspended dielectric particles	50–300 kHz	10^{-21}	Arvanitakis & Geraci	frequency
Pulsar timing	10^{-9} Hz	10^{-15}	Jenet	frequency
Bulk accoustic wave resonators	1 MHz–GHz	$10^{-22} / \sqrt{\text{Hz}}$	Goryachev & Tobar	frequency
Heterodyne amplification of magnetic conversion signals	3 GHz	10^{-32}	Li	frequency
Cosmic microwave background polarisation	10^{-16} Hz	$R > 0.22$	Polnarev	frequency
Interaction with binary orbits	$10^{-8} - 10^{-6}$ Hz	10^{-11}	Mashoon	frequency
Spacecraft Doppler tracking	$10^{-5} - 10^{-8}$ Hz	$10^{-14} - 10^{-15}$	Armstrong	frequency
Superconducting rings/Sagnac effect	GHz	no prediction	Anandan, Chiao	frequency
Oscillation of Cosserat rods	$10^{-4} - 1$ Hz	$2 \cdot 10^{-21}$	Tucker & Wang	TRL0
Torsion bar	10^{-2} Hz	$3 \cdot 10^{-19}$	Ando	sensitivity
Skyhook	10^{3} Hz	$3 \cdot 10^{-17}$	Braginsky & Thorne	sensitivity

C. Technology development items

The following three pages are a summary of the technology items identified as being required for a laser interferometry space mission (both payload and spacecraft elements).

The compilation lists, for each identified item, the relevant system/sub-system, the associated development area, the top-level technology risks (and related comments), any relevant funded activity, and an assessment of the current TRL and an associated recommended action.

The summary has been compiled by Martin Gehler (ESA), with inputs from the Committee. Although the table remains incomplete in some details, the principle technologies and their status are fully covered.

Out of these 40 or so items, the 4 high priority and 3 medium priority technology development activities are described in further detail in Section 5.

System	Development Area	Technology Item	Comments	Top Level Technology Risks	Funded Activity	Current TRL Recommended Action
Gravitational Reference Sensor: LPF mission will demonstrate the core technologies of the GRS Potential improvements: lifetime, mass/volume, efficiency, upgraded electronics.						
	Charge Control	Charge Management	Have Hg-lamps. Long wave length affects system robustness. Lamps have ageing problems. Strongly prefer LEDs	UVLED wavelength (≤240 nm), lifetime, flight qualification, high frequency modulation	Charge Management for LISA, Deep UV LED feasibility study	4 (3 for LED) Technology of UV LED likely to evolve over the next few years.
	Front-end electronics	Front end electronics	Requires delta-stability and testing at 0.1 mHz. Stability at 1 mHz less demanding than LPF	Low frequency (<3 mHz) performance	GRS FEE characterization for LISA	4 Analogue technology not expected to improve. However current technology sufficient.
Laser System						
Alternative I: Low Power master laser; high fidelity phase modulator; high power amplifier.	**Amplifier Phase Fidelity**					
	Modulation	Phase Fidelity of amplifiers at GHz frequencies	Fidelity needed to transmit clock noise over the constellation. Characterization of the amplifier required - if it fails, amplifier technology to be develped		High Power Laser for LISA	4 **High priority.** Test of amplifier is ongoing. Status promising. Failure of method may require development of long lead
	Source Ia	Laser source	Single space qualified laser source available in Europe. Industrial Policy.		High Power Laser for LISA	4 An industrial issue. Consider international collaboration for non european suppliers
	Source Ib	External Cavity Laser (ECL) as source, (possibly) internal frequency moduation and fiber amplifier	Compact, robust, low power, low mass components	Demonstrate system requirements, lifetime, environmental qualification and system integration	Laser vendor working on source, GSFC working on amplifier	4 (NASA) Optimize ECL design, rebuild and stabilize amplifier, system integration and testing.
Alternative II: High power master laser; high power, high fidelity phase modulator	**Source**	2W Single stage laser	No amplifier needed			
	Modulation	Phase modulator	Current phase modulators with GHz bandwidth can not handle 2W laser power (LiNbO3-based, could try RTP) Insertion losses too high.			
General issues with laser system: No clear preference for alternative I vs II		Laser frequency stabilization	Not a major issue, multiple options exist (US-Aerospace company, ESA TRP for cavity/ locking, arm locking).Reference located on OB(?). PDH in phasemeter for GRACE-FO.	Frequency stability in the high power beam		Part of optical system design. Does not require new technology
		Power Stabilization		Power stabilization, flight qualified voltage reference		
		Lifetime		Element and subsystem lifetime		Demonstration might be needed for life of pump diode
		Redundancy		A/B switching device	Optical Bench Development for LISA	
		Subsystem Integration		Modulator, fiber coupling, beam dumps, isolators,		

ESA L3: compilation of technology development items (1/3)

Telescope						
Alternative I: Off-axis Expected advantage: Reduced stray light **Alternative II: On-axis Expected advantages: pm-stability, manufacturability, mass/volume**			No major issues brought up by eLISA technology evaluation			
	Optical imaging	Focus stability	μm-stability or on bench telescope latest plans: focus mechanism	Manufacturability		
	pm-stability	Materials with sufficiently low CTE and thermal modeling	Lab experiments have shown pm-stability for various materials in temperature stable environment	Optical pathlength stability	Opto-Mechanical Stability Characterization	4 Completed
	Stray light	Stray light from optical surfaces and contamination	Secondary mirror is main contributor in on-axis system. UF studies show that this can be suppressed. Tertiary and quarternary mirrors dominate off-axis systems.	Time-varying stray light affects phase	Stray light measurements at UF. Stray light modeling and measurements at GSFC	3 Preliminary measurements of masks demonstrate effect
General issues with telescope and imaging system. No clear preference for alternative I vs II.		Point ahead mechanism		Actuator, tilt-to-piston	PAAM development	5 Finished, two parallel contracts
	Alternative I	Optic. Assembly Track. Mech.	Pointing the optical assembly requires actuator, pivots and launch locks.	In-field guiding, pointing mechanism		GSFC demonstrated a TRL 9 actuator to move the optical
	Alternative II	In-field Pointing	Actuator together with telescope design impacts	actuator (medium), telecope properties		
Optical Bench		Dual FIOS Demonstration			Running, mid 2016. Target TRL 5	4 depending on outcome of study
Includes: Fiber output from 2W laser, Backlink fiber, beam expanding telescope, local interferometer, reference interferometer, long baseline interferometer, beam reducing/imaging optics for photo detectors, photo detectors, point ahead actuator.		Demonstration of interferometric imaging, telescope simulator, and phase center offset control			Running, mid 2016. Target TRL 5	4 depending on outcome of study
		Beam Expander	Main issue: Stray light (see telescope)			
		Acquisition Sensor	Might have been identified already?			
		Photodetector	Imaging system, mechanical mount (photo diodes should be part of phasemeter system)			Early development reccommended. Medium priority
	Baseline: Monolithic bench	Manufacturing	Manufacturing technology for high optical component-density to be demonstrated. Robot fabrication?	Manfacturing rate, repairability, assembly/disassembly	Optical Bench Development for LISA	**High priority.** Early funding in industry/institute consortium to develop the process
	Alternative: Modular Bench	Feasibility/Design	Has not been explored in any detail			
		Back-link fiber Demonstration	Non reprocity noise, if not solved, may force to in-field pointing with single optical bench. Highly impacting design constrain	Reciprocity/dual frequency/ phase	System:OB:Backlink Phase Referencing	**High priority.** Funding to institute for experimental proof of principle
Propulsion: μN Thrusters			No immediate action recommended by LISA technology evaluation. Cold gas usage set a mass constraint. Lighter alternatives desirable			
	Alternative I	Colloids	Propellant storage/supply, subsystem refinements, lifetime, manufacturability	Lifetime	Propellant subsystem at TRL 5 by 2016	4
	Alternative II	μRITS	Conversion from millinewton to micronewton		Ongoing delta-qualification for Euclid backup	4 for LISA application
	Alternative III	Cold gas	Compare against L3 mission requirements to verify readiness.		Cold Gas Propulsion	9 for GAIA, flying on LPF, 4-5 for LISA pending TRL assessment

ESA L3: compilation of technology development items (2/3)

Phase measurement system:	**TDI-Demonstration**					
	Measures beat signal between two lasers; frequency range: 2-30MHz (pending on mission design). Measures beat signal between sidebands at same frequency range to synchronize clocks and measure ADC timing jitter. Measures ranging tone. Might also be used for data	Phasemeter: Base line design	FPGA-based. Was NASA responsibility within old LISA Arrangement. Demonstrated at JPL/ Florida at the time. Demonstration on NGGM. A ESA led eLISA may require an European one.	Will this technology be available 20yrs from now?	Metrology System for LISA	5 Bring to flight qualification from demonstrated breadboard level
		Phasemeter: Alternative designs	Current phasemeter is FPGA based. This decision was made 10+ years ago. Is this still the best technology?			
		Clock synchronization/ Pilot tone	Test from three individual clocks to phase meter data. Some demonstrations in the US.		Ongoing work at AEI (not sure about funding)	
		Ranging	Different options: TDI ranging w. or w/o low-f tone or PRN ranging,			
		Photo detector	Need quad detector with good AC response up to 30MHz			
		Arm locking	If Needed: Integration with pre-stabilization?			
		Frequency stabilization	Use heterodyne interferometry (demonstrated at UF). Could be integrated into phasemeter		Used in LIGO-related experiments at UF.	
		front end electronics	Work done at AEI and JPL at least, but DLR making flight hardware for GRACE-FO that meets LISA requirements, with a need for slightly increased BW. Design started with AEI LISA desgin		GRACE-FO	6+ (GRACE-FO)
System issues						
Lock Acquisition	**Initial alignment**	Study	Has been studied at NASA at some level for LISA	Design implications known too late		
	Initial frequency locking	Adds requirements to phasemeter and lasers (predetermined frequencies)	Some demonstrations at JPL and AEI	Design implications known too late		
Orbits and orbital mechanics	**Orbits optimization**	Design criteria	What would be the goal: Small angular variations, constellation lifetime, small beat frequencies or cost of orbit insertion?			
	Separation from prop module	Avionics	Separation will add angular and linear momentum to SC. Can μN thrusters take them out? Or are gyros required? Do we need/have Reaction wheels?	Dynamic range of thrusters		
Architecture study	**Explore parameter space**	Still many options: Cross-over (reduces stray light issues), third laser to measure differential laser noise (solves back-link fiber), location of in-field guiding system (range vs. beam size), …		Solve problems we don't have and ignore problems we have.		Architecture study

NASA Investments

NASA has invested consistently in the following technologies for a gravitational wave mission:

Laser system, Telescopes, Colloidal micronewton thrusters

Phase measurement systems, used to demonstrate Time Delay Interferometery

The joint US-German Laser Ranging Interferometer has resulted in developments of:

Frequency stabilized laser system (Cavity, master laser, and stabilization electronics using the Phasemeter. System is not redundant)	6+
Phasemeter (4 channels, including differential wavefront sensing, and phase locking, but without clock tone). Uses Phasemeter algorithms from LISA	6+
Quadrant photoreceiver (4 pW/rt(Hz) from 4-16 MHz)	6+
(Optical bench, which is not LISA-like)	6+
Intererometer link acquisition without a dedicated sensor (GW mission likely would use a sensor, but algorithms without have been thought through in great detail for GRACE-FO)	(algorithms)

ESA L3: compilation of technology development items (3/3)

D. Relation of space and ground

The LISA Cornerstone proposal of 1995 grew out of the community that had already won approval for the LIGO, Virgo, and GEO600 ground-based gravitational wave detectors, augmented with scientists who had expertise in previous space missions and proposals. Because the typical wavelength of gravitational waves observable by a LISA-like mission is 10^5 times longer than the best LIGO wavelength, the science is very different. LIGO cannot detect sources heavier than about $1000M_{\odot}$, because more massive systems radiate only at lower frequencies. So the exploration of the massive black holes that inhabit most galaxies, their merger history and formation over cosmological time, is the domain of LISA-like missions.

However, both LIGO and LISA/eLISA are based on the technology of laser interferometry, and there is significant overlap in their experimental communities. The LISA proposal is led by AEI/Hannover, which also participates in LISA Pathfinder and the GRACE follow-on. And AEI/Hannover operates GEO600, where a number of the principal technologies that were used to upgrade initial LIGO to Advanced LIGO were developed and tested. AEI/Hannover also provided Advanced LIGO with its powerful lasers.

The University of Glasgow provided Advanced LIGO with its monolithic mirror suspensions, and it used many of the same key technologies to build the optical bench for LISA Pathfinder. The University of Florida demonstrated one of the first length-sensing schemes for Advanced LIGO, delivered its 'input optics' system, and developed the optical layout for advanced LIGO's main interferometer, including the design of the recycling cavities. For LISA, University of Florida tested time delay interferometry and measured the stability of various materials for the telescope. Much of the data analysis development for LISA-like missions (including organising the Mock LISA Data Challenge) was performed by groups that have also made key contributions to LIGO data analysis, for example those at Montana State University, the University of Birmingham, and AEI/Potsdam.

The success of Advanced LIGO not only validates the principle of laser interferometry for gravitational wave detection; much more importantly, it should be taken as a spectacular demonstration of the capabilities of some of the key experimental and data analysis groups that also support the LISA/eLISA proposals. Coupled with the early successes of the LISA Pathfinder mission, which demonstrates the technology of free-fall needed by LISA (which has no heritage in LIGO), there should be considerable confidence that the LISA community is capable of delivering a successful gravitational-wave observatory in space.

E. Acronyms

AIV: Assembly, Integration, and Verification
BH: black hole
CMB: Cosmic Microwave Background
CWD: Compact White Dwarf
D/SRE: Director of Science and Robotic Exploration (ESA)
E–ELT: European Extremely Large Telescope
eLISA: evolved Laser Interferometer Space Antenna
EM: Engineering Model
EMRI: Extreme Mass Ratio Inspiral
EQM: Engineering Qualification Model
EW: electro-weak (interaction)
FEEP: Field Emission Electric Propulsion
GOAT: Gravitational Observatory Advisory Team (this Committee)
GRS: Gravitational Reference Sensor
ICSO: innermost stable circular orbit
IMS: Interferometry Measurement System
IPC: Industrial Policy Committee (ESA)
LHC: Large Hadron Collider
LIGO: Laser Interferometer Gravitational Wave Observatory (US)
LISA: Laser Interferometer Space Antenna
LRI: Laser Randing Interferometer (Grace Follow-On)
LSST: Large Synoptic Survey Telescope
MBH: massive black hole
MBHB: massive black hole binary
MLDC: Mock LISA Data Challenge
NGO: New Gravitational wave Observatory (scaled-down LISA)
NS: neutron star
PEM phase: Payload Engineering Model phase
PFM: Proto-Flight Model
SKA: Square Kilometre Array
S/N: signal-to-noise ratio
SPC: Science Programme Committee (ESA)
SSC: Senior Science Committee (ESA)
TDA: Technology Development Activity
TRL: Technology Readiness Level
WD: white dwarf

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